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Filmwise Condensation of Steam on Horizontal
Corrugated and Wire-Wrapped Corrugated Tubes

by

Matthew B. Long
Lieutenant, United States Navy
B.S., University of Washington, 1985

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

June, 1993

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REPORT DOCUMENTATION PAGE				
1a Report Security Classification: Unclassified		1b Restrictive Markings		
2a Security Classification Authority		3 Distribution/Availability of Report		
2b Declassification/Downgrading Schedule		Approved for public release; distribution is unlimited.		
4 Performing Organization Report Number(s)		5 Monitoring Organization Report Number(s)		
6a Name of Performing Organization Naval Postgraduate School		6b Office Symbol (if applicable) 34		7a Name of Monitoring Organization Naval Postgraduate School
6c Address (city, state, and ZIP code) Monterey CA 93943-5000		7b Address (city, state, and ZIP code) Monterey CA 93943-5000		
8a Name of Funding/Sponsoring Organization		6b Office Symbol (if applicable)		9 Procurement Instrument Identification Number
Address (city, state, and ZIP code)		10 Source of Funding Numbers		
		Program Element No	Project No	Task No
11 Title (include security classification) FILMWISE CONDENSATION OF STEAM ON HORIZONTAL CORRUGATED AND WIRE WRAPPED CORRUGATED TUBES(Unclassified)				
12 Personal Author(s) Matthew B. Long				
13a Type of Report Master's Thesis		13b Time Covered From To		14 Date of Report (year, month, day) June 1993
15 Page Count 146				
16 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
17 Cosati Codes		18 Subject Terms (continue on reverse if necessary and identify by block number)		
Field	Group	Subgroup		
19 Abstract (continue on reverse if necessary and identify by block number) Heat transfer performance of horizontal roped tubes was studied using an evaporator/condenser test rig. The condenser section contained a single horizontal tube and was operated at both vacuum and atmospheric conditions. A vacuum pump was integral to the system to ensure the presence of noncondensable gasses did not affect the results. The test tubes were Wolverine MHT Korodense titanium tubes with an outside diameter of 16.07 mm and a corrugation pitch of 8 mm. The effect of wire-wrapping was studied using titanium wires ranging from 0.1 to 1.6 mm in diameter corresponding to a range of pitch to diameter ratio from 80 to 5. The outside heat transfer coefficient, h_o , was determined by first experimentally obtaining the overall heat transfer coefficient, U_o , and then utilizing a modified Wilson Plot procedure. Results obtained for steam condensation indicate that the MHT Korodense titanium tube provides negligible enhancement compared to the a titanium tube. The addition of wire-wrapping provided minimal increase in the outside heat transfer coefficient about 8% at a fractional coverage of approximately 5% corresponding to a pitch to wire diameter ratio near 20.				
20 Distribution/Availability of Abstract _X_ unclassified/unlimited __ same as report __ DTIC users		21 Abstract Security Classification Unclassified		
22a Name of Responsible Individual Paul J. Marto		22b Telephone (include Area Code) (408) 656-2989		22c Office Symbol ME/Mx

ABSTRACT

Heat transfer performance of horizontal roped tubes was studied using an evaporator/condenser test rig. The condenser section contained a single horizontal tube and was operated at both vacuum and atmospheric conditions. A vacuum pump was integral to the system to ensure the presence of noncondensable gases did not affect the results. The test tubes were Wolverine MHT Korodense titanium tubes with an outside diameter of 16.07 mm and a corrugation pitch of 8 mm. The effect of wire-wrapping was studied using titanium wires ranging from 0.1 to 1.6 mm in diameter corresponding to a range of pitch to diameter ratio from 80 to 5. The outside heat transfer coefficient, h_o , was determined by first experimentally obtaining the overall heat transfer coefficient, U_o , and then utilizing a modified Wilson Plot procedure.

Results obtained for steam condensation indicate that the MHT Korodense titanium tube provides negligible enhancement compared to a titanium tube. The addition of wire-wrapping provided minimal increase in the outside heat transfer coefficient, about 8% at a fractional coverage of approximately 5% corresponding to a pitch to wire diameter ratio near 20.

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NOMENCLATURE

a	as defined in equation (4.30)
A_i	effective inside surface area, m^2
A_o	effective outside surface area, m^2
b	as defined in equation (4.26)
c	as defined in equation (2.22)
c_p	specific heat at a constant pressure, J/kg-K
c_8	as defined in equation (2.14)
C_i	leading coefficient for the inside heat transfer correlation used
C_n	as defined in equation (2.8)
d	as defined in equation (2.23)
d_o	external groove diameter, m
D_i	tube inside diameter, m
D_o	tube outside diameter, m
D_w	wire diameter, m
e	groove depth, m
E_1	as defined in equation (2.32)
E_2	as defined in equation (2.33)
E_3	as defined in equation (2.35)
f	as defined in equation (2.30)
F	as defined in equation (2.4)
g	gravitational constant, 9.81 m/s
h_{fg}	specific enthalpy of vaporization, J/kg

h_i	inside heat transfer coefficient, W/m^2-K
h_o	outside heat transfer coefficient, W/m^2-K
h_{oe}	outside heat transfer coefficient for enhanced tubes, W/m^2-K
h_{os}	outside heat transfer coefficient for smooth tubes, W/m^2-K
k_c	thermal conductivity of the coolant film, $W/m-K$
k_f	thermal conductivity of the condensate film, $W/m-K$
k_m	thermal conductivity of the tube material, $W/m-K$
K_1	as defined in equation (2.26)
K_2	as defined in equation (2.27)
L	active length of tube exposed to steam, m
L_o	external groove depth, m
L_1	length of inlet portion of tube, m
L_2	length of outlet portion of tube, m
LMTD	log mean temperature difference, K
m	Reynolds number exponent
$\dot{m}$	mass flow rate of the coolant, kg/s
m_1	as defined in equation (4.25)
n	Prandtl number exponent
n_t	number of tubes in a vertical row
Nu	Nusselt number
P	corrugation pitch, m
P_w	wire-wrap pitch, m
P_{sat}	saturation pressure, Pa
Pr	Prandtl number

Pr_w	Prandtl number at the wall temperature
PW	as defined in equation (2.10)
Q	heat transfer rate, W
q	heat flux, W/m^2
r	tube specific constant as defined for equation (2.30)
R	radius of curvature of corrugation ridge, m
R_f	fouling resistance, K/W
R_i	inside thermal resistance, K/W
R_o	outside thermal resistance, K/W
R_{total}	total thermal resistance, K/W
R_w	wall thermal resistance, K/W
Re	Reynolds number
Re_f	Reynolds number for the condensate film
$Re_{2\phi}$	two phase Reynolds number
T_{cf}	temperature difference across the condensate film, K
ΔT_{cf}	temperature difference across the film, K
T_m	mean coolant bulk temperature, K
T_{sat}	vapor saturation temperature, K
T_{wo}	outside wall temperature, K
T_1	cooling water inlet temperature, K
T_2	cooling water outlet temperature, K
U_o	overall heat transfer coefficient, W/m^2-K
U_∞	vapor velocity, m/s
V_w	coolant velocity, m/s
x	Reynolds number exponent in equation (4.15)
X	as defined in equation (4.24)

Y	as defined in equation (4.23)
Z	as defined in equation (4.19 or 4.20)
Z^*	as defined in equation (2.9)

Greek Symbols

α	leading coefficient for the outside heat transfer correlation used
$\acute{\alpha}$	helix angle measured from the tube axis
β	as defined in equation (2.37)
ϵ	as defined in equation (2.25)
ϵ_T	enhancement ratio based on ΔT for wire-wrapped smooth tubes
ϵ_{TC}	enhancement ratio based on ΔT for wire-wrapped corrugated tubes
γ	as defined in equation (2.29)
Γ	mass flow rate of condensate per unit length of horizontal condenser tube
μ_c	dynamic viscosity of the coolant, kg/m-s
μ_f	dynamic viscosity of the condensate film, kg/m-s
μ_w	dynamic viscosity of condensate at the wall, kg/m-s
η	surface efficiency
Φ_c	as defined in equation (2.14)
ω	tube specific constant as defined for equation (2.10)
Ω	as defined in equation (4.15, 4.16 or 4.17)
ρ_f	density of the condensate film, kg/m ³
ρ_v	density of the vapor, kg/m ³

- σ_f surface tension of the condensate at film temperature,
lb_f/ft
- θ severity factor
- θ^* tube specific constant as defined for equation (2.9)

ACKNOWLEDGEMENTS

The author would like to express his sincere appreciation to Professor Paul J. Marto and Professor Stephen B. Memory for their advice, guidance, and continual support towards the completion of this thesis.

Many thanks is also given to Mr. Tom McCord and the workers in the Mechanical Engineering Department Machine Shop for their timely fabrication of all the required materials necessary to complete this endeavor.

The author wishes to extend his greatest appreciation and thanks to his wife, Laura. Without her extreme patience, love, and encouragement this project would not have been possible.

I. INTRODUCTION

A. BACKGROUND

Reductions in size, weight and cost have become increasingly important design considerations in the development of every component destined for use aboard United States Navy vessels. Significant reductions in weight have already been achieved for main propulsion machinery with the advent of the gas turbine propulsion plant. Weight reduction is also possible through redesign of auxiliary systems and other large components such as main steam condensers. The use of heat transfer enhancement techniques for condenser tubing has been one avenue receiving considerable attention in the pursuit of this goal. Smaller more efficient condensers would result in reductions in capital cost, space requirements, weight and operating cost.

The four primary factors that affect the performance of condensers are the thermal resistances on the coolant side, across the tube wall, the vapor side, and also that due to fouling. Each can be reduced to minimize its effect, which in turn enhances the overall heat transfer rate of the system. In experimental studies, the fouling resistance can be neglected if the tube is thoroughly clean prior to testing.

Enhancement techniques can be categorized into two major groups, active and passive. Guido [Ref. 1] compiled a fairly comprehensive listing of both groups of enhancement techniques for the tube side heat transfer rate. Passive techniques such as internal helical ribbing and displaced promoters (the use of wire mesh or HEATEX inserts) will be discussed in detail in a later section. It should be noted, however, that both of these techniques have a corresponding increase in pumping power requirements. Wall thermal resistance can be reduced passively by decreasing the wall thickness or changing the tube material. Similar to enhancement techniques for the tube side, the shell side resistance can also be reduced by both active and passive means. The passive enhancement techniques of wire-wrapping and tube corrugation will also be covered in a later section.

A variety of corrugated or roped tubes are available for use in condenser applications. Figure 1 shows the profile of one type of corrugated tube which has a groove radius smaller than the ridge radius. Wolverine Tube Company manufactures a low pressure drop (LPD) and a maximum heat transfer (MHT) tube of this type (trade name: Korodense), available for commercial use. The MHT tubes have a larger groove depth compared to the LPD tubes [Ref. 2]. Other types of corrugated tubes are also available which have a larger groove radius than the ridge radius. Marto et al. [Ref. 3] present test results on various other corrugation geometries.

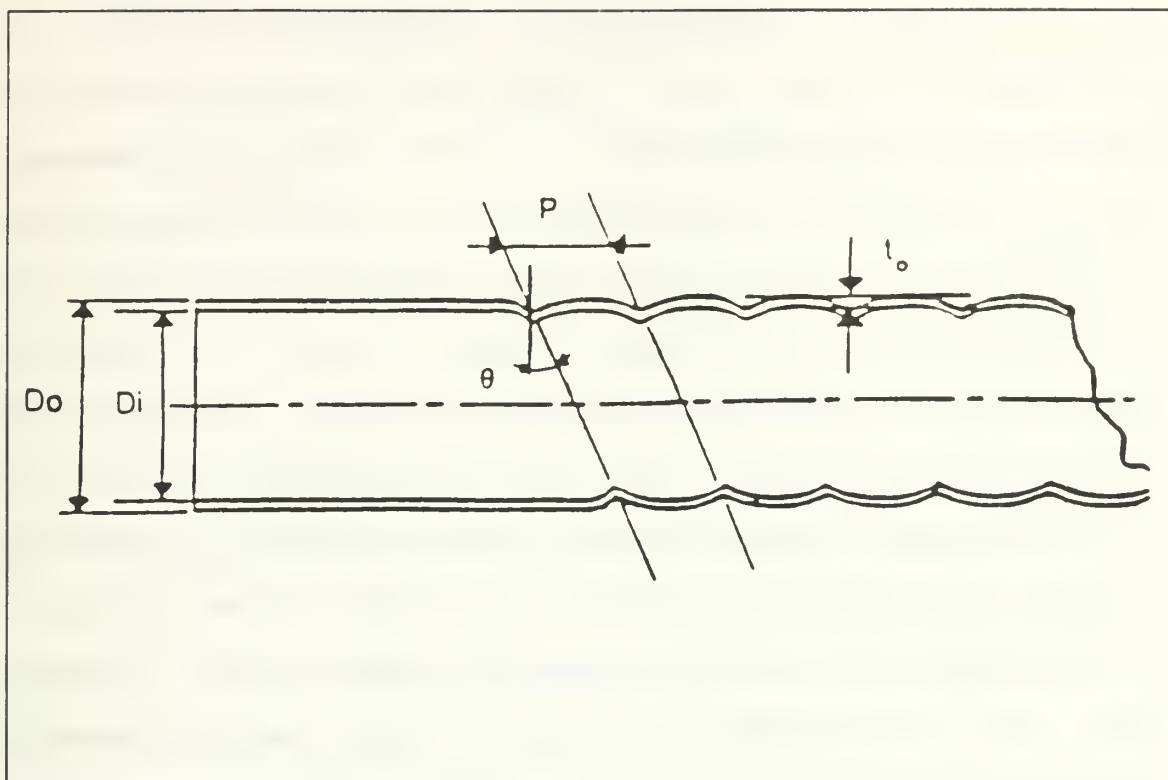


Figure 1. Profile of a corrugated tube

B. CONDENSATION APPLICATIONS FOR ENHANCED TUBES

In 1971 Withers and Young [Ref. 4] performed a theoretical analysis on a power plant main condenser. Their findings indicated a substantial saving in almost every condenser aspect if the smooth tubes were replaced by Korodense roped tubes. Similar results were obtained by Webb et al. [Ref. 5]. They indicated a possible 30 to 40 percent increase in the overall heat transfer coefficient when analyzing a tube-for-tube replacement of smooth to Korodense tubes. This benefit was calculated for two separate power plants of different heat duty. An ongoing comprehensive study of 14 Tennessee Valley

Authority (TVA) power plant condensers, retubed with corrugated tubes, has yielded significant economic and performance benefits [Refs. 6 and 7]. Of the 14 condensers retubed by TVA, their Gallatin Unit 1 has provided long-term results with over 12 years of successful operation since retubing. In 1983 Boyd et al. [Ref. 8] studied the performance of TVA's Gallatin Unit 1 plant after only three years of operation. Their findings yielded up to a 43% increase in the overall heat transfer coefficient when clean tubes were analyzed. However, data also indicated that the corrugated tubes fouled quicker than plain tubes. Rabas et al. [Ref. 9] studied 12 of the retubed TVA condensers and found fouling rates for the enhanced tubes ranging from about the same as to almost twice that experienced in plain tubes. Although the fouling rates were higher, Rabas et al. [Ref. 9] reported the fouling resistance values for the LPD Korodense tubes never exceeded the minimum allowable TEMA standard.

Union Carbide [Ref. 10] performed analysis on roped condenser tubes with a Thin Film Condensing Promoter (T.F.C.P.), which is essentially a wire-wrapped roped tube. Their findings indicated an increase in the heat transfer coefficient by a factor of between 2 to 3 times that found with a smooth tube under condensate loaded conditions.

C. NAVAL POSTGRADUATE SCHOOL CONDENSATION RESEARCH

Titanium has a number of properties which make it a desirable alternative to the conventional copper-nickel tubing currently in use today on board Naval vessels. Its high strength to weight ratio enables the tubes to be designed with a much thinner wall thickness, while still maintaining the durability of the overall system. Titanium also has a high resistance to erosion and sea water corrosion. This leads to reduced shutdown time for tube cleaning and replacement. One of the primary disadvantages of titanium tubing is its poor thermal conductivity. Titanium has approximately 50% the thermal conductivity of copper-nickel [Ref. 11]. This disadvantage can be partially offset by a decreased wall thickness and also through the use of enhanced surfaces. The Naval Postgraduate School (NPS), in conjunction with the Naval Surface Warfare Center, Carderock Division, Annapolis Detachment, has been testing the enhancement characteristics of various types of titanium tubing.

In order to examine the heat transfer characteristics of various types of enhanced tubes, a suitable test platform must be utilized. While the ideal test platform would be a full scale model of the actual condenser used in the field, the cost associated with such an apparatus would be prohibitive. The condensation test platform, constructed by Krohn [Ref. 12] at NPS, has been in use since 1982. Although several modifications have been made by various researchers since that

time, the overall apparatus and the operation remain basically unchanged. Van Petten [Ref. 13] lists a comprehensive summary of the work completed by eight NPS researchers from 1982 through 1987. Most of the work concentrated on the performance of various types of externally finned tubes. Mitrou [Ref. 14], in addition to studying finned tubes, also performed experiments on wire-wrapped smooth copper tubes. More recent work conducted by Coumes [Ref. 15], Guttendorf [Ref. 16] and Swensen [Ref. 17] dealt with further studies of finned copper tubes. O'Keefe [Ref. 18] studied the performance of various titanium tubes. His tests included smooth tubes, wire-wrapped smooth tubes, LPD Korodense tubes, and wire-wrapped LPD Korodense tubes. Other researchers including Kanakis, Brower and Mazzone [Refs. 19-21] have studied tube bundle configurations for smooth and corrugated tubes, both with and without wire-wrapping.

D. OBJECTIVES

The main objectives of this study are as follows:

1. To verify the repeatability of the calculated coefficients for both coolant side and vapor side heat transfer correlations obtained by previous researchers on wire-wrapped smooth and corrugated titanium tubes.
2. To manufacture and collect condensation data on smooth and MHT Korodense titanium tubes with varying fractional coverage due to wire-wrapping.
3. To determine if any relationship exists for optimal fractional coverage or pitch to diameter ratio between wire-wrapped smooth tubes and wire-wrapped MHT and LPD Korodense tubes.

II. LITERATURE SURVEY

A. INTRODUCTION

Condensation on horizontal tubes has been an intensely studied heat transfer mechanism throughout the years. New developments in condenser tubing require continued experimental and theoretical research in this field.

There are two fundamental modes of condensation on horizontally mounted condenser tubes, filmwise and dropwise. Dropwise condensation can produce heat transfer rates as much as an order of magnitude larger than those associated with filmwise condensation. Various surface coatings have been developed in order to promote dropwise condensation and take advantage of the higher heat transfer rates. However, with time these coatings lose their effectiveness and filmwise condensation eventually returns. For this reason, condenser design calculations are normally based on the more conservative filmwise mode of condensation [Ref. 22].

Internally, the primary factors affecting thermal resistance are the intensity of turbulence and the thermal conductivity of the coolant medium. The degree of turbulence can be changed by altering the internal tube wall geometry or through the use of displacement promoters.

B. VAPOR SIDE CONSIDERATIONS

Condensation on horizontal tubes consists of a complex two phase process. A suitable theoretical model must be utilized in order to accurately predict these phenomena.

1. Horizontal Smooth Tubes

Nusselt [Ref. 23] developed the foundation for the study of filmwise condensation on horizontal tubes in 1916. His work was formulated for a quiescent vapor condensing on a single horizontal tube. Due to the increase in the thickness of condensate as gravity forces it around the sides of the tube, the local heat transfer coefficient decreases around the tube circumference. Nusselt developed a theory for the average heat transfer coefficient around the tube, accounting for the lower resistance at the top of the tube where the film was the thinnest and the higher resistance at the bottom of the tube where the film was the thickest. As a result, he developed the following equation:

$$h_o = 0.728 \left[\frac{k_f^3 g \rho_f (\rho_f - \rho_v) h_{fg}}{\mu_f D_o (T_{sat} - T_{wo})} \right]^{1/4} \quad (2.1)$$

where the fluid properties are evaluated at the film temperature, given by:

$$T_f = \frac{1}{3} T_{sat} + \frac{2}{3} T_{wo} \quad (2.2)$$

Nusselt's theory has been extensively studied since 1916, and with the imposed assumptions, has been found to be

generally valid [Refs. 24, 25]. It has also been found to be accurate for cases which do not conform to Nusselt's original assumptions, such as variable wall temperature [Ref. 26]. One of the major problems encountered in applying Nusselt's theory in the design of condensers arises from his assumption of a quiescent vapor. While in theory, and in some limited practical applications, the assumption of a stationary vapor can be justified, most steam condensers operate under conditions where the vapor is travelling at some constant velocity.

With the vapor in motion, sufficient shear forces can be developed which significantly thin the condensate film and increase the outside heat transfer coefficient. Early theoretical work by Shekriladze and Gomelaury [Ref. 27], which accounted for vapor shear, resulted in the following equation to approximate the mean Nusselt number.

$$\frac{Nu}{Re_{2\phi}^{1/2}} = 0.64 (1 + (1 + 1.69 F)^{1/2})^{1/2} \quad (2.3)$$

where:

$$F = \frac{g D_o \mu_f h_{fg}}{U_\infty^2 k_f (T_{sat} - T_{wo})} \quad (2.4)$$

and the two phase Reynolds number is given by:

$$Re_{2\phi} = \frac{\rho_f U_\infty D_o}{\mu_f} \quad (2.5)$$

Lee and Rose [Ref. 28] compared vapor shear models with experimental results and found that the Shekriladze-Gomelaouri results were more conservative than more rigorous developments performed by other researchers due to their simplified approximation for the interfacial shear stress. Fujii et al. [Ref. 29], in a more recent study, performed an extensive development on the outside of a horizontal tube. From experimental data, they also developed an empirical formulation for the condensation of steam on a horizontal tube which includes vapor velocity effects:

$$\frac{Nu}{Re_{2\phi}^{1/2}} = 0.96 F^{1/5} \quad (2.6)$$

where F and $Re_{2\phi}$ are defined in equations (2.4) and (2.5). For situations where the surface shear forces dominate, equation (2.6) tends to more accurately predict the vapor side heat transfer coefficient for steam.

As discussed previously, the primary modes of external tube enhancement covered in this study are wire-wrapping and the addition of helical grooves. Both methods have associated advantages and disadvantages.

2. Wire-Wrapped Smooth Tubes

The benefits of wire-wrapping smooth tubes have been attributed to two primary effects: the thinning of the condensate film between the wires due to surface tension forces and the better drainage of the condensate along the

wire, (Fujii et al. [Ref. 30] and Marto et al. [Ref. 31])). Thomas [Ref. 32] conducted tests on vertical tubes with wires attached vertically along the tubes and demonstrated this latter enhancement effect. Horizontal smooth tubes with coiled wire were later studied by Thomas et al. [Ref. 33] and their findings indicated a two fold increase in the heat transfer coefficient over that predicted by Nusselt theory for a smooth tube. Marto et al. [Ref. 31] determined an optimum wire pitch to diameter ratio between 5 and 7 for steam condensation. They achieved an enhancement between 1.5 and 1.8 for the heat transfer coefficient over plain tubes.

For low surface tension fluids (R-11 and ethanol), Fujii et al. [Ref. 30] obtained results 2 to 3 times those predicted by Nusselt theory, with an optimum wire pitch to diameter ratio of 2. O'Keefe [Ref. 18] compared the enhancement ratio versus fractional coverage (the percentage of the tube's surface covered by wire) on a titanium smooth tube. Together with data obtained by Mitrou [Ref. 14] and Sethumadhavan and Rao [Ref. 34], he determined that the optimum fractional coverage was between 10 and 30%. This fairly broad range of values was attributed to the possible effects of the different tube material thermal conductivities used in the studies.

3. Corrugated Tubes

In 1971, Withers and Young [Ref. 35] performed a design study of two condenser bundles with heat duty of 25 million Btu/hr, one with bare (smooth) tubes and the other with corrugated (roped) tubes. Coolant flow pressure drop was one of the matching parameters for the comparison. This requirement made it necessary to use a larger corrugated tube (1.00 inch outside diameter (OD)), than the smooth tube (0.75 inch OD). They found an enhancement of 88% for the outside bundle heat transfer coefficient. Catchpole and Drew [Ref. 36] tested single corrugated tubes and determined that the steam side heat transfer coefficient increased with increasing groove density and passed through a maximum with increasing groove depth. Their conclusion was that the smaller the helix angle (measured from the tube axis), the worse the condensate drainage, resulting in a reduction of the outside heat transfer coefficient. Similar results were reported by Marto et al. [Ref. 3] and Mehta and Rao [Ref. 37]. Eleven different corrugated tubes of three primary types were tested by Marto et al. [Ref. 3]. Within each corrugation type, the largest value for the outside heat transfer coefficient was obtained at small pitch to diameter ratios (P/D). As P/D increased, the enhancement ratio decreased. In tests conducted by Mehta and Rao [Ref. 37], they found the condensing coefficient enhancement ratio decreased from 1.26 to 1.1 when the corrugation groove pitch was increased from 6.35 mm to 12.5 mm

with a constant groove depth of 0.63 mm. They also tested the effect of holding the groove pitch to groove depth ratio constant. A maximum enhancement ratio of 1.38 was achieved with the smallest groove depth and pitch. Zimparov et al. [Ref. 38] confirmed the same trend, using 27 mm outside diameter corrugated tubes, with the enhancement ratio increasing from 0.99 to 1.22 for a corrugation groove pitch decreasing from 16.9 mm to 6.5 mm.

Cunningham and Bahjernejad [Ref. 39] examined the effects of condensate inundation on corrugated tube bundles. They tested two different multistart tubes, one with two helical starts and the other with six starts. Their results indicated severe limitations in performance due to inundation effects for tube bundles more than a few rows deep. Additional inundation tests were conducted on multistart tubes by Cunningham and Boudinar [Ref. 40]. They reported similar results as those of Cunningham and Bahjernejad [Ref. 39], and additionally found that the more severe the indentation (groove depth) on the roped tube, the greater was the reduction in vapor side heat transfer for the tube bundle.

Rabas [Ref. 41] studied an extensive data bank of results published by numerous researchers. He found that the enhancement in the outside heat transfer coefficient was negligible for tubes with grooved geometries that are suitable

for ball cleaning¹ of the inside surface. He also compared the collected data with the results predicted by three different correlations. The Wolverine correlation [Ref. 2]:

$$h_o = 0.725 C_n \left[\frac{k_f^3 \rho_f^2 g h_{fg}}{n_t \mu_f D_o (T_{sat} - T_{wo})} \right]^{1/4} \quad (2.7)$$

where:

$$C_n = Z^* [n_t]^{PW} \quad (2.8)$$

$$Z^* = 38 (\sigma_f)^{0.65} + \frac{\theta^*}{\mu_f} \quad (2.9)$$

and:

$$PW = \left[(5.31E-7) + [0.195 (\omega)^{0.932/\mu_f}]^6 \right]^{1/6} \quad (2.10)$$

- Values for ω and θ^* are listed for specific tube geometries by Wolverine in Reference 2.
- The variable C_n in Equation (2.7) must be applied using English units.

and the correlation developed by Mehta and Rao [Ref. 37]:

$$\frac{h_o}{(k_f^3 \rho_f^2 g / \mu_f^2)^{1/3}} = 1.54 e^{205\theta} \left(\frac{4\Gamma}{\mu_f} \right)^{-0.33e^{-7.5\theta}} \quad (2.11)$$

for $0 < \theta < 15 \times 10^{-4}$, and:

¹ball cleaning is a method of removing deposits from the inside of condenser tubes by periodically recirculating sponge rubber balls through the tubes with the coolant.

$$\frac{h_o}{(k_f^3 \rho_f^2 g / \mu_f^2)^{1/3}} = 1.92 e^{-13.2\theta} \left(\frac{4\Gamma}{\mu_f} \right)^{-0.33 e^{-7.5\theta}} \quad (2.12)$$

for $15 \times 10^{-4} < \theta < 200 \times 10^{-4}$, were both found to overpredict the outside heat transfer coefficient. Values similar to those obtained from the experimental data were predicted by the Yorkshire correlation [Ref. 42] given by:

$$h_o = c_8 \left[\frac{k_f^3 \rho_f^2 g}{\mu_f \Gamma} \right]^{1/3} \quad (2.13)$$

where:

$$c_8 = 1 + \Phi_c \left[\frac{L_o}{D_o} \right] \left[\frac{P}{D_o} \right]^{-0.75} \quad (2.14)$$

and Φ_c varies with tube profile and can be found in Reference 42. However, Rabas [Ref. 41] cautioned its use due to the results being close to unity. In conclusion, he recommended using smooth tube correlations and neglecting the minimal enhancement associated with corrugated tubes for design calculations.

Dreitser et al. [Ref. 43] determined a correlation for the enhancement ratio of corrugated tubes based on three primary geometric ratios: 1) The ratio of the radius of curvature of the corrugation ridge to the outside diameter, R/D_o ; 2) the ratio of groove pitch to the outside diameter, P/D_o ; and 3) the ratio of the external groove diameter to the outside diameter, d_o/D_o .

$$\frac{h_{os}}{h_{os}} = 2.469 \left(1 - 0.2445 \frac{R}{D_o} \right) \left(1 - 0.379 \frac{P}{D_o} \right) \exp \left[3.65 \left(1 - \frac{d_o}{D_o} \right) \right] \quad (2.15)$$

They found that if any of the three ratios were increased while keeping the others constant, the enhancement ratio would decrease.

Cunningham and Fidler [Ref. 44] made a comparative study of the effects of vapor shear on multistart corrugated tubes and smooth tubes. They found that the corrugated tubes maintained their enhancement advantage over the smooth tube when subjected to increased vapor velocity.

4. Wire-Wrapped Corrugated Tubes

Wire-wrapping of corrugated tubes has been shown by various researchers to significantly reduce the effect of condensate inundation (Memory et al. [Ref. 45], Union Carbide [Ref. 10], and Marto and Wanniarachchi [Ref. 46]).

Union Carbide [Ref. 10] tested steam condensation for a wire-wrapped roped tube in a bundle arrangement. They reported nearly identical performance for both the unloaded and the condensate loaded conditions tested. Condensing coefficients approximately 2.5 times that of plain tube results were achieved for the condensate loaded condition. Memory et al. [Ref. 45] obtained a 60 to 68% enhancement over smooth tube results when condensing R-113 on a wire-wrapped roped tube bundle arrangement containing four tubes in a

vertical column. Their tests indicated an optimal wire pitch to diameter ratio of 7.5.

O'Keefe [Ref. 18] tested the enhancement effects of three different wire diameters (1.6 mm, 1.0 mm, and 0.5 mm) when used to wrap an LPD Korodense tube. Enhancements ranging between 20 and 30% above smooth tube results were obtained with the maximum obtained for the 0.5 mm wire with a wire pitch to wire diameter ratio of 14.

C. COOLANT SIDE CONSIDERATIONS

1. Smooth Tubes

Numerous correlations have been developed for use in the analysis of the coolant side heat transfer correlation associated with the turbulent flow regime inside a pipe ($Re > 10,000$). Many of the earlier correlations have been presented in the form:

$$Nu = C_i Re^m Pr^n \quad (2.16)$$

This form has been used for several well-known correlations including those developed by Dittus and Boelter [Ref. 47]:

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (2.17)$$

and Colburn [Ref. 48]

$$Nu = 0.023 Re^{0.8} Pr^{1/3} \quad (2.18)$$

A correction factor for equation (2.18) was developed by Sieder and Tate [Ref. 49]:

$$Nu = 0.027 Re^{0.8} Pr^{1/3} (\mu_c / \mu_w)^{0.14} \quad (2.19)$$

This modification compensates for the variation in the coolant viscosity when large temperature differences exist between the bulk coolant and the inner tube wall temperature. All fluid properties for equations (2.17), (2.18), and (2.19) are evaluated at the mean coolant bulk temperature, T_m .

$$T_m = \frac{(T_1 + T_2)}{2} \quad (2.20)$$

In more recent years, Sleicher and Rouse [Ref. 50] and Petukhov [Ref. 51] developed equations (2.21) and (2.24) respectively, which are applicable over a wider range of Prandtl numbers.

$$Nu = 5 + 0.015 Re_f^c Pr_w^d \quad (2.21)$$

where:

$$c = 0.88 - \frac{0.24}{4 + Pr_w} \quad (2.22)$$

$$d = \frac{1}{3} + 0.5 \exp(-0.6 Pr_w) \quad (2.23)$$

and,

$$Nu = \frac{(\epsilon/8) Re Pr}{K_1 + K_2 (\epsilon/8)^{1/2} (Pr^{2/3} - 1)} \quad (2.24)$$

where:

$$\epsilon = (1.82 \log(Re) - 1.64)^{-2} \quad (2.25)$$

$$K_1 = 1 + 3.4\epsilon \quad (2.26)$$

$$K_2 = 11.7 + 1.8 Pr^{-1/3} \quad (2.27)$$

Lorenz et al. [Ref. 52] compared their experimental results for cold water (i.e. large Prandtl number) with seven of the more common inside heat transfer correlations. They found that the Petukhov-Popov and Sleicher-Rouse correlations agreed to within 5% of the experimental data. The other correlations typically underpredicted the data by between 5 and 15%.

2. Corrugated Tubes

The internal ridges of the tube wall produced when manufacturing corrugated tubes cause two primary effects. The irregularity of the wall surface results in an increased frictional effect and causes the flow to swirl, thereby requiring additional pumping power to achieve flow rates equal to similar diameter smooth tube flow. The increase in turbulence also has the effect of increasing the inside heat transfer rate. In the study by Withers and Young [Ref. 35], the total inside enhancement ratio of the tube bundle tested was 56% above that obtained for a smooth tube bundle designed with an equal pressure drop. Catchpole and Drew [Ref. 36] found the inside heat transfer coefficient to increase with increasing groove depth and groove frequency. However, they

stressed that the increase in performance was obtained at the expense of significantly greater friction factors and therefore increased pumping power and operating cost. In comparing their results with the Prandtl analogy [Ref. 53] they found that, due to the turbulence caused by the presence of grooves, the inside heat transfer coefficient followed the trend predicted by the Prandtl analogy.

Mehta and Rao [Ref. 37] presented their findings in terms of the severity factor, the ratio of groove depth squared to the product of groove pitch and inside diameter. This dimensionless group was chosen because it has been found to be a useful criterion for evaluation of heat transfer and frictional characteristics of plain and spirally enhanced tubes. An improvement of 260% was obtained above smooth tube results with the higher inside heat transfer coefficient corresponding to higher severity factors. Of the eleven tubes tested by Marto et al. [Ref. 3], inside enhancement was reported for all the tube geometries examined, with the magnitude ranging from 1.6 to 5.1 times a smooth tube. Zimparov et al. [Ref. 38] tested nine tubes with differing corrugation geometries and obtained results similar to previous researchers. They achieved inside enhancement ratios between 1.77 and 2.73, with an increase in the friction factor of 2 to 4 fold.

For corrugated tubes, Withers [Ref. 54] modified existing correlations and developed the following:

$$Nu = \frac{\sqrt{f/8} Re Pr}{7.22(P/D_i)^{-1/3} \sqrt{Pr} [(e/D_i)Re\sqrt{f/8}]^{0.127} + \gamma} \quad (2.28)$$

where:

$$\gamma = - \left[2.5 \ln \left(2 \frac{e}{D_i} \right) + 3.75 \right] \quad (2.29)$$

and:

$$\sqrt{\frac{f}{8}} = - \frac{1}{2.46 \ln [r + (7/Re)^m]} \quad (2.30)$$

The variables m and r were determined for each tube by a curve-fitting procedure. He obtained agreement between experimental and predicted data to within 10%. Wolverine currently utilizes a form of this correlation in their Engineering Data Book II [Ref. 2].

In a comparison of the LPD and MHT Korodense tubes manufactured by Wolverine [Ref. 2], they report a 25% higher inside heat transfer coefficient for the MHT Korodense tube than for the LPD Korodense tube. The MHT Korodense tube also has twice the pressure drop of the LPD Korodense tube.

After compiling an extensive collection of published data, Rabas et al. [Ref. 55] recommended a minor modification to the leading coefficient in the Yorkshire correlation [Ref. 42] to better fit the experimental data. The Yorkshire correlation is similar in form to equation (2.17) with an

additional complex leading coefficient (E_1) to compensate for the corrugation tube geometry.

$$Nu = 0.027 E_1 Re^{0.8} Pr^{0.4} \quad (2.31)$$

where:

$$E_1 = 1.0 + 1.182 E_2 E_3 / (P/D_i)^{0.7} \quad (2.32)$$

$$E_2 = \cos(\alpha) \quad (2.33)$$

$$\alpha = \tan^{-1}(P/\pi D_i) \quad (2.34)$$

$$\ln(E_3) = - \sum_{j=0}^3 a_j [\ln(e/D_i)]^j \quad (2.35)$$

and:

$$a_0 = 5.0766, \quad a_1 = 4.4224, \quad a_2 = 1.1240, \quad a_3 = 6.700 \times 10^{-2}$$

The modification by Rabas et al. [Ref. 55] changed the exponent in equation (2.32) from 0.7 to 0.406.

Panchal and France [Ref. 56] conducted a study of large pitch spirally indented tubes for possible application to pressure drop sensitive systems. Their data resulted in internal enhancements as high as 100% over smooth tube data and they reported agreement within a 20% error band for the results predicted by the correlation proposed by Mehta and Rao [Ref. 57], given by:

$$Nu = \frac{\sqrt{f/2} Re Pr}{\beta Pr^{0.55} (Re\sqrt{f/2})^{0.11} + \gamma} \quad (2.36)$$

where:

$$\beta = 9.4 (P/D_i)^{-0.15} (e/D_i)^{0.11} \quad (2.37)$$

and γ is defined as in equation (2.29). It should be noted that β in equation (2.37) is constant for any given tube configuration.

3. Tubes With Inserts

Numerous types of inserts are available for use in enhancing the inside heat transfer coefficient. Some of the types used by previous researchers at NPS include: twisted tape, wire-wrap, and HEATEX (a wire mesh insert supplied by CAL GAVIN). A number of correlations have been developed for determining the inside heat transfer coefficient when using these various inserts [Refs. 58-60]. These correlations for HEATEX, however, are for specific loop densities of the wire matrix and are not universally valid. HEATEX inserts not only significantly increase the overall heat transfer rates, but also inhibit fouling. Gough and Rogers [Ref. 61] presented results collected from a condenser fitted with HEATEX inserts which was in operation for over four years without being shut down for cleaning. Their findings indicated the actual fouling resistance was over 96% less than the allowable limits after a service life of 26 times that of the original unit

with no insert. However, it should be noted that the use of an insert has a pronounced effect on increasing the pressure drop across the tube. Inserts are used in experimental applications to realize a larger temperature drop in the coolant flow, thus decreasing the uncertainty of the heat transfer calculations.

III. EXPERIMENTAL APPARATUS

A. SYSTEM OVERVIEW

The apparatus used for this research was originally constructed by Krohn [Ref. 12]. The initial design has been modified by several previous researchers (in particular Swensen [Ref. 17]) and has been used successfully by Coumes [Ref. 15], Guttendorf [Ref. 16], Swensen [Ref. 17] and O'Keefe [Ref. 18] to test condensation on single horizontal tubes of various configurations. Figure 2 contains a general schematic of the overall system. The boiler, a 0.30 meter diameter Pyrex glass cylinder, contains ten 4 kW, 440 Volt Watlow immersion heaters which are used to generate steam from distilled water. From the boiler, steam passes up through a cylindrical section of Pyrex glass with an inside diameter of 0.15 meters and a length of 2.13 meters. Two 90 degree Pyrex glass elbows redirect the steam back down a second similar cylindrical section of 1.52 meters in length. The steam then enters the stainless steel test section containing the horizontal condenser tube mounted as shown in Figure 3. The test section also contains a circular glass viewing port so the condensation process can be observed while conducting tests. Excess steam, not condensed on the sample tube, passes through the test section and into the final Pyrex glass

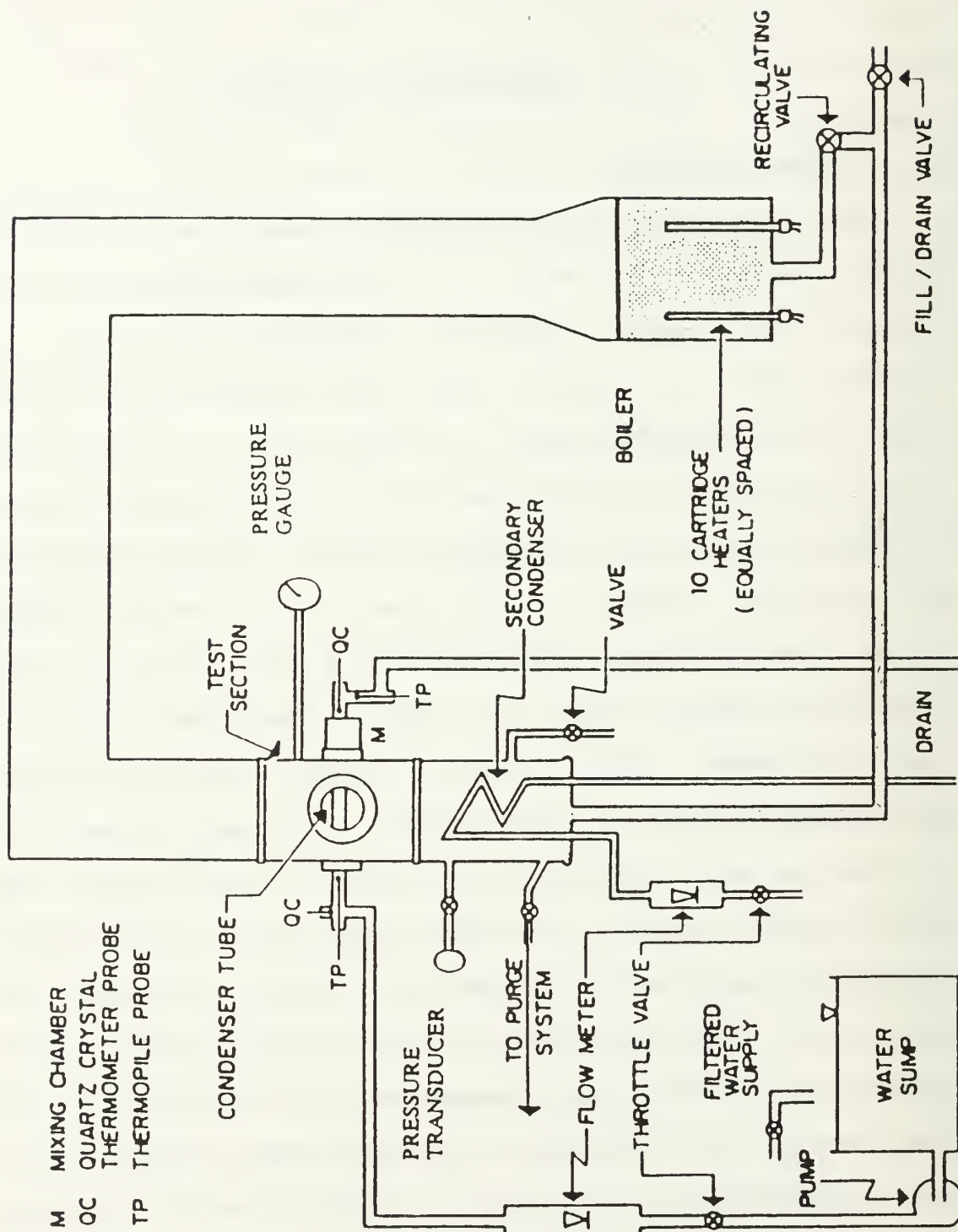


Figure 2. Schematic of the Single Tube Test Apparatus

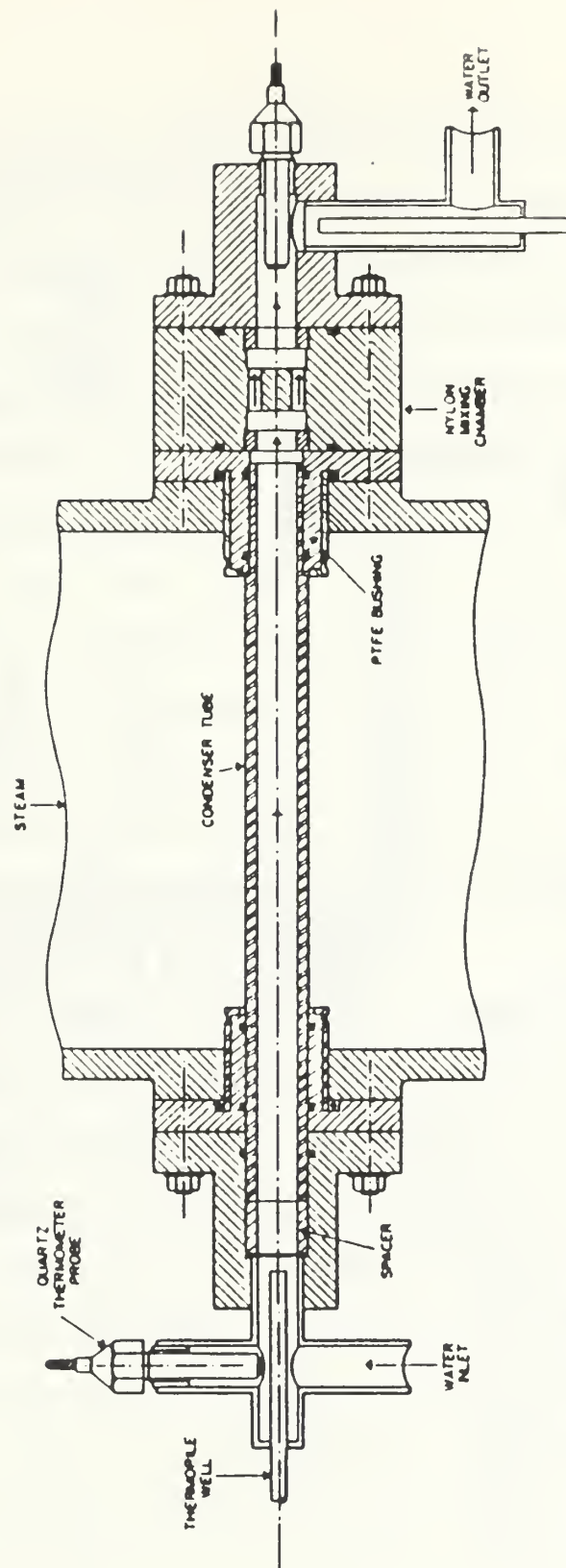


Figure 3. Schematic of the Test Section

cylinder containing an auxiliary condenser. The auxiliary condenser section collects all the condensate, where it returns to the boiler via a gravity drain in the baseplate.

Cooling water for the single horizontal tube in the test section was supplied by two centrifugal pumps connected in series and drawing suction from an adjacent cooling water sump. A throttling valve and calibrated flowmeter allowed for control of the cooling water flow rate. The auxiliary condenser cooling water was supplied directly from the building water main. After setting the desired coolant flow rate through the single horizontal tube, the saturation temperature in the test section was controlled by adjusting the throttle valve on the auxiliary condenser coolant flow line.

A suction port at the base of the auxiliary condenser section allowed for the removal of non-condensable gases. Figure 4 shows a schematic of the associated system. Non-condensibles drawn from the auxiliary condenser passed through an internal condensing coil where, any associated steam that might be present was condensed and collected in a plexiglass vacuum chamber for later removal. The non-condensibles then passed through the vacuum pump and were expelled to the atmosphere.

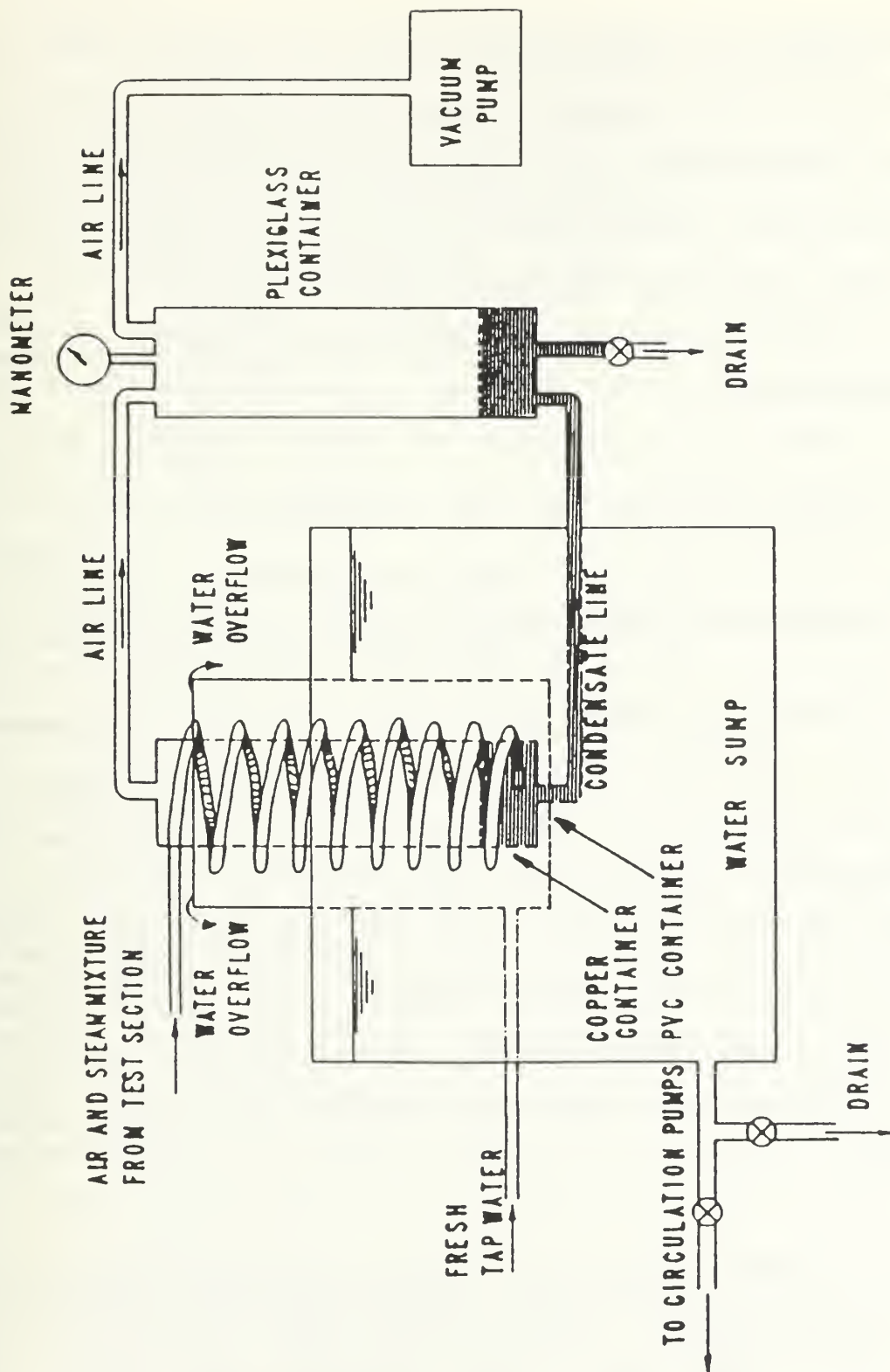


Figure 4. Schematic of the Purging System and Cooling Water

B. SYSTEM INSTRUMENTATION

The 440 Volt immersion heater power supply was controlled by a silicon controlled rectifier mounted on the electrical switchboard. Poole [Ref. 62] details the power calculation for the input into the data acquisition system.

Three separate methods were used to monitor the pressure of the system:

1. Setra model 204 pressure transducer.
2. System saturation temperature converted into pressure.
3. Heise solid front pressure gage (visual reference only).

Temperature measurements were obtained using several devices. The vapor temperature of the system was measured by a Teflon coated and a metal sheathed type-T copper/constantan thermocouple located just upstream of the horizontal tube being tested. Condensate return and ambient temperatures were also measured with Teflon coated type-T copper/constantan thermocouples. The inlet and outlet coolant temperature of the condenser test tube were measured with three separate probes:

1. A Teflon coated type-T copper/constantan thermocouple.
2. A ten junction, Teflon coated type-T copper/constantan thermopile.
3. An HP 2804A quartz crystal thermometer.

The three temperature probes at the outlet of the horizontal tube were located downstream of a mixing chamber in order to obtain a representative average coolant discharge temperature. Figure 3 contains the locations of these temperature probes.

An HP-3497A data acquisition system, linked to a HP-9826A computer, was used to collect the voltage readings from all the measurement devices. The data collection and reduction program "DRPML", listed in Appendix C, allowed for the processing and storage of all the data by the HP-9826A computer.

Swensen [Ref. 17] provides calibration data for the pressure transducer, thermocouples, quartz thermometer and flowmeter.

C. TUBES TESTED

Eight enhanced tubes were manufactured for this thesis. Tests were also conducted on tubes studied by previous researchers to ensure repeatability of results. Table I contains a listing of all the tubes tested and additional tubes used in the comparison of results. All of the tubes assembled for this study were made from a single titanium MHT Korodense tube manufactured by Wolverine. Seven of the tubes were then wrapped with wire having diameters ranging from 0.1 to 1.6 mm to test enhancement effects. To attach the wire to the tubes, two different methods were used. The larger diameter (stiffer) wires (≥ 0.5 mm) were wrapped around a rod

of a smaller diameter than the tube, this formed the wire into a tight coil. The wire was then fed onto the tube by twisting the coil and advancing it along the groove of the tube. The wire was then spot welded in place at each end of the active condensing surface. For the wires < 0.5 mm, one end was spot welded to the tube at the edge of the active surface. The wire was then tightly wrapped around the tube, by hand, in the groove and spot welded to the other end of the active surface. Both methods resulted in a constant wire pitch equal to the corrugation pitch of the tube. The wire was not physically attached to the active tube surface and did not act as a fin. The additional tubes included in Table I were manufactured for research conducted by O'Keefe [Ref. 18] and Mitrou [Ref. 14].

Table I. LISTING OF TUBES TESTED

Tube No.	Tube Type	Wire Diameter (mm)	Wire Spacing (mm)	Wire Pitch (mm)	P_w/D_w Ratio	Fractional Coverage	Outside Diameter (mm)	Inside Diameter (mm)	Tube Material
M	MHT	None	None	None	None	0	16.07	13.53	Titanium
MW16	MHT	1.6	6.40	8.00	8.00	0.200	16.07	13.53	Titanium
MW10	MHT	1.0	7.00	8.00	8.00	0.125	16.07	13.53	Titanium
MW05	MHT	0.5	7.50	8.00	16.00	0.063	16.07	13.53	Titanium
MW04	MHT	0.4	7.60	8.00	20.00	0.051	16.07	13.53	Titanium
MW03	MHT	0.3	7.70	8.00	26.67	0.038	16.07	13.53	Titanium
MW02	MHT	0.2	7.80	8.00	40.00	0.025	16.07	13.53	Titanium
MW01	MHT	0.1	7.90	8.00	80.00	0.013	16.07	13.53	Titanium
L	LPD	None	None	None	None	0	15.85	13.47	Titanium
LW05	LPD	0.5	6.50	7.00	14.00	0.074	15.85	13.47	Titanium
ST0	Smooth	None	None	None	None	0	15.85	13.86	Titanium
ST1	Smooth	0.5	7.60	8.10	16.80	0.062	15.85	13.86	Titanium
ST2	Smooth	0.5	3.46	3.96	7.92	0.120	15.85	13.86	Titanium
SC1	Smooth	0.5	3.13	3.63	7.26	0.141	19.05	12.71	Copper

*Fractional coverage in this thesis is the ratio of the product of the wire diameter and the wire length on the active surface to the total active surface area.

IV. EXPERIMENTAL PROCEDURES AND DATA ANALYSIS

A. TUBE PREPARATION

To ensure consistent results in data collection, a continuous film of condensate must be present over the entire tube surface. A chemical treatment procedure used by Guttendorf [Ref. 16] and several other researchers at NPS was used to produce filmwise condensation on the tube surface. Prior to installation into the test section, the tube was chemically treated as follows:

1. The inside and outside of the tube were thoroughly cleaned with mild soap using a soft bristle brush. The soap was rinsed off with distilled water, then the tube was rinsed with acetone. Distilled water was again poured over the tube, to ensure the water formed a continuous film on the tube surface. If breaks in the film were observed (an indication of impurities on the tube surface) the cleaning process was repeated. Once a continuous film was present, the active surface was not handled, thus minimizing the possibility of contamination.
2. The tube was then placed in a steam bath.
3. A solution of 50% by weight sodium hydroxide and ethyl alcohol was mixed for treating the tube surface. The solution was kept warm to ensure a watery consistency.
4. The solution was then applied over the tube surface, with a small brush, in 10 minute intervals for one hour. While applying the solution, the tube was rotated so the entire surface could be treated. If the tube was treated previously, the solution was only applied every 5 minutes over a 20 minute period.
5. After the tube surface was treated, it was removed from the steam bath and rinsed with distilled water to remove any excess alcohol/sodium hydroxide solution. To verify

a continuous film will be produced in the presence of steam, the tube was returned to the steam bath, to ensure the entire surface wets easily.

6. Without touching the active surface, the tube was removed from the steam bath and immediately mounted in the test section of the boiler apparatus. If tests were to be conducted with an insert, the insert was installed prior to securing the coolant flow piping to the test section.

The oxide layer formed by the chemical treatment promotes a continuous film on the tube surface. Due to the negligible thickness of the oxide film, its thermal resistance was considered insignificant compared to the overall thermal resistance of the tube.

B. SYSTEM START-UP AND SHUTDOWN PROCEDURES

After the tube has been installed in the test section, the system can be brought on-line using the following procedures:

1. The boiler section must be filled with distilled water to a level approximately 4 to 6 inches above the top of the heater elements. The boiler can be filled by attaching a hose from the distilled water tank to the piping at the boiler drain/fill valve. Opening the vent valve on the auxiliary condenser allows for gravity filling of the boiler. To drain the boiler, disconnect the distilled water tank hose and attach the hose leading to the drain in bilge area below the boiler. Then open the drain/fill valve and allow the water to gravity drain from the boiler.
2. When the appropriate water level has been achieved, shut both the fill/drain valve and the vent valve on the auxiliary condenser.
3. Energize the data acquisition system, computer, printer, and quartz thermometer power supply. Load the software program DRPML and check for proper operation. Then verify that the thermocouple outputs all correspond to the same ambient temperature.

4. Open the fill valve to the cooling water sump and adjust the flow rate to ensure the drain box does not overflow. The fill valve for the sump is located to the left of the boiler switchboard.
5. Perform a leak test on the cooling water systems.
 - a. Energize the cooling water supply pumps and adjust the rotameter flow rate from 20% to 80% while checking for leaks in the test section. Then secure the control valve and de-energize the cooling water supply pumps.
 - b. Open the control valve for the auxiliary condenser and adjust the flow rate to at least 30% and check for leaks in the system. After completing the leak check, reset the flow rate to the auxiliary condenser to the desired position, minimum of 10%.
6. Place the system under a vacuum. To do this, shut the drain valve in the plexiglass cold trap and energize the vacuum pump. Check the pressure gage on the vacuum pump to ensure proper operation and open the suction valve located on the side of the auxiliary condenser. After the vacuum pump has reduced the system pressure to below 3 psia, shut the suction valve and secure the vacuum pump.
7. With the system under a vacuum, the heaters may be energized . Three switches must be placed in the "ON" position to energize the heaters.
 - a. Switch #3 on panel p5, in the main hallway adjacent to room H-106.
 - b. The heater load bank circuit breaker on the left side of the boiler heater switchboard.
 - c. The condensing rig boiler power switch, on the front of the boiler heater switchboard.

When the heaters are energized, the power level should be adjusted to 50 Volts, using the silicon control rectifier on the boiler control switchboard. If the system is below 2 psia, the power level should initially set to 40 Volts to minimize vibrational shock to the system caused from vapor bubble formation and collapse. As the system warms up, the power can be increased, in increments of 10 Volts, until the desired setting is reached.

8. After the system pressure rises above 4 psia, non-condensable gases need to be purged from the system. This can be accomplished by following the procedures outlined in step 6. Throughout the purging procedure, the horizontal tube coolant flow should remain secured, while the flow rate to the auxiliary condenser can be adjusted until all the gases have been evacuated. When the auxiliary condenser is warm to the touch everywhere, and condensate has formed in the plexiglass container, most of the non-condensable gases have been removed. The initial purging of the system may take between 15 and 30 minutes. This process should be repeated every few hours during extended operation.
9. To establish filmwise condensation on the tube being tested, the following steps should be performed:
 - a. Allow the system vapor temperature to increase to $\approx 90^{\circ}\text{C}$ (at least 3800 microvolts on channel 40).
 - b. Increase the flow rate in the auxiliary condenser to 50% or 60% and allow the vapor temperature to reduce to $\approx 75^{\circ}\text{C}$ (approximately 3200 microvolts).
 - c. Secure coolant flow to the auxiliary condenser and allow the vapor temperature to increase to about 85°C (≈ 3700 microvolts). This forms a steam blanket over the tube.
 - d. Initiate coolant flow of 80% in the single horizontal tube.
 - e. Adjust the auxiliary condenser flow rate to maintain the desired temperature and pressure for data collection.

If, after performing steps 9 a. through 9 e., some dropwise condensation persists, repeat step 9 again. If dropwise condensation continues, the tube should be removed, cleaned and retreated in accordance with the procedures listed in section IV. A. A cutout section in the insulation above the test section allows for a light to be shown on the upper surface of the tube in order to check for a continuous film on the tube surface.

10. Run the software program DRPML by pressing the "RUN" key on the keyboard. The program will prompt you with questions for the necessary information required to run as listed by O'Keefe [Ref. 18] and in Appendix C.

11. Ensure the system has been operating at steady-state conditions for at least 30 minutes prior to continuing past the question "Enter the flowmeter reading".
12. Vacuum runs are conducted at a heater setting of 90 Volts and 1980 ± 10 microvolts on channel 40. This corresponds to $T_{\text{Sat}} \approx 48^{\circ}\text{C}$, and a vapor velocity of ≈ 2 m/s.
13. The atmospheric runs are conducted at a heater setting of 175 Volts and 4280 ± 10 microvolts on channel 40. This corresponds to $T_{\text{Sat}} \approx 100^{\circ}\text{C}$, and a vapor velocity of ≈ 1 m/s. Special care must be used when operating at atmospheric pressure to ensure over-pressurization and rupture does not occur.
14. When taking readings, double check the flowmeter reading prior to accepting any data point. If both vacuum and atmospheric pressure runs are to be conducted in the same day, the vacuum data should be collected first. This eliminates the long cool down time required after an atmospheric pressure run.

After data has been collected, the system should be secured utilizing the following procedures:

1. Secure power to the heating elements. Turn off the switches in the reverse order listed in step 7 of the start-up procedures.
2. Secure coolant flow to the auxiliary condenser. If the system is to remain at vacuum pressure until the next data run, then the auxiliary condenser can be used in assisting to cool the system down, provided the same tube will be used for the following test.
3. Secure the coolant flow through the single horizontal tube by securing the coolant pumps.
4. Secure the water flow to the coolant sump tank.
5. To return the system to atmospheric pressure, slowly open the vent valve on the auxiliary condenser. To avoid contaminating the system, keep any foreign material away from the vicinity of the vent valve during this procedure.
6. If an emergency should arise, such as an over-pressurization or breakage, ensure the heater power

is secured first. Then, let the system cool down prior to checking for damage.

C. DATA COLLECTION PROCEDURE

After the tube has been installed and the system has been operating for a minimum of 30 minutes, data collection may begin. Each run consisted of data points taken at coolant flow rate settings from 80% to 20% and back up to 80%, in 10% increments. This allowed for each data point to be checked for repeatability during the run. Before a data point was accepted, sample readings were taken to ensure the coolant temperature difference, the overall heat transferred, and the saturation temperature were stable. The temperature difference between the inlet and outlet coolant flow must be stabilized (± 0.01 °C) prior to recording data. After setting the coolant flow rate, the aforementioned parameters required between 5 and 15 minutes to stabilize.

D. DATA REDUCTION PROCEDURE

For a slice of the condenser tube, the overall thermal resistance from vapor to coolant can be represented by the sum of the coolant side resistance (R_i), the fouling resistance (R_f), the wall resistance (R_w), and the vapor side resistance (R_o), as shown in equation (4.1).

$$R_{total} = R_i + R_f + R_w + R_o \quad (4.1)$$

Only clean tubes were tested so the fouling resistance was set to zero, therefore:

$$R_{total} = R_i + R_w + R_o \quad (4.2)$$

Being convective in nature, the vapor and coolant side resistances can be expressed as follows:

$$R_o = \frac{1}{h_o A_o} \quad (4.3)$$

$$R_i = \frac{1}{h_i A_i} \quad (4.4)$$

The wall resistance term comes from the general radial conduction equation for a concentric cylinder:

$$R_w = \frac{\ln(D_o/D_i)}{2\pi L k_m} \quad (4.5)$$

The total thermal resistance can be expressed in terms of the overall heat transfer coefficient (U_o) and the effective outside condensing area (A_o), as follows:

$$R_{total} = \frac{1}{U_o A_o} \quad (4.6)$$

The effective outside condensing area of the tube can be calculated using the following equation:

$$A_o = \pi D_o L \quad (4.7)$$

For the inside effective area, two different conditions are present. The area corresponding to the outside effective area, where heat transfer takes place radially, and the inlet

and outlet portions of the tube, where heat removal occurs axially. To account for this 'fin' effect, the extended fin assumption and associated fin efficiencies were used in the following expression:

$$A_i = \pi D_i (L + L_1 \eta_1 + L_2 \eta_2) \quad (4.8)$$

Substituting equations (4.3), (4.4), and (4.6) into equation (4.2) yields the following:

$$\frac{1}{U_o A_o} = \frac{1}{h_i A_i} + R_w + \frac{1}{h_o A_o} \quad (4.9)$$

From the data collected, the total heat transfer rate across the tube can be calculated directly from an energy balance using the coolant mass flow rate and the coolant temperature difference (from inlet to outlet) through the tube:

$$\dot{Q} = \dot{m} c_p (T_2 - T_1) \quad (4.10)$$

The total heat transfer rate can also be expressed in terms of the overall heat transfer coefficient, the effective outside condensing area, and the log mean temperature difference (LMTD):

$$\dot{Q} = U_o A_o (LMTD) \quad (4.11)$$

where:

$$LMTD = \frac{(T_2 - T_1)}{\ln \left[\frac{T_{sat} - T_1}{T_{sat} - T_2} \right]} \quad (4.12)$$

The measurements for LMTD were obtained in the following manner:

- T_1 was measured from a quartz thermometer installed at the inlet section of the coolant flow for the condenser tube.
- T_2 was measured with a quartz thermometer inserted downstream of the mixing chamber at the outlet section of the coolant flow for the condenser tube. A correction factor was applied to T_2 in order to compensate for viscous heating of the coolant through the tube. The corrections, which depend on the inside geometry of the tube, the coolant flow velocity, and the type of insert, are listed in Appendix A.
- T_{sat} was measured using the vapor thermocouple (channel 40).

Substituting equation (4.10) into equation (4.11) provides determination of the overall heat transfer coefficient directly from experimental measurements:

$$U_o = \frac{\dot{m}C_p(T_2 - T_1)}{A_o(LMTD)} \quad (4.13)$$

With A_o , A_i , R_w , and U_o all known quantities, the only remaining unknowns in equation (4.9) are h_o and h_i , the outside and inside heat transfer coefficients. The modified Wilson plot technique was used to calculate these coefficients.

E. MODIFIED WILSON PLOT TECHNIQUE

In 1915, Wilson [Ref. 63], developed a method for indirectly determining the inside and outside thermal

resistance from an overall resistance. Wilson's method requires the heat flux of the system to remain constant. While this application proves valid in theory, difficulties arise when trying to maintain a constant heat flux while varying the cooling water velocity, Marto [Ref. 64].

Khartabil et al. [Ref. 65] provide a comprehensive listing of modifications to the original technique developed by Wilson. For a detailed development of the modified Wilson plot technique, the reader is referred to Marto [Ref. 64] and Marto and Nunn [Ref. 66].

Using the modified Wilson plot method to determine the inside and outside heat transfer coefficients requires one to choose a general form for each correlation. The program DRPML enables the user to select from several options. The inside heat transfer coefficient correlation can be written in simplified form as follows:

$$h_i = C_i \Omega \quad (4.14)$$

where Ω varies with the particular correlation used. Using the Sieder-Tate correlation [Ref. 49] (equation (2.19)):

$$\Omega = \frac{k_c}{D_i} Re^x Pr^{1/3} (\mu_c/\mu_w)^{0.14} \quad (4.15)$$

where the program allows the Reynolds number exponent (x) to be varied. Using the Sleicher-Rouse correlation [Ref. 50] (equation (2.21)):

$$\Omega = \frac{k_c}{D_i} (5 + 0.015 Re_f^c Pr_w^d) \quad (4.16)$$

where c and d are defined in equation (2.22) and (2.23) respectively. Using the Petukhov-Popov correlation [Ref. 51] (equation (2.24)):

$$\Omega = \frac{k_c}{D_i} \left[\frac{(\epsilon/8) Re Pr}{K_1 + K_2 (\epsilon/8)^{1/2} (Pr^{2/3} - 1)} \right] \quad (4.17)$$

where ϵ , K_1 , and K_2 are defined in equation (2.25), (2.26), and (2.27) respectively.

Similarly, the outside heat transfer coefficient correlation may be written in simplified form:

$$h_o = \alpha Z \quad (4.18)$$

where Z can be selected from equation (2.1) (Nusselt's theory [Ref. 23]):

$$Z = \left[\frac{k_f^3 g \rho_f^2 h_{fg}}{\mu_f D_o (T_{sat} - T_{wo})} \right]^{1/4} \quad (4.19)$$

or from equation (2.62) (Fujii's correlation [Ref. 29]):

$$Z = \frac{k_f}{D_o} F^{1/5} Re_{2\phi}^{1/2} \quad (4.20)$$

F and $Re_{2\phi}$ are defined in equation (2.4) and (2.5) respectively.

Substituting equation (4.14) and (4.18) into equation (4.9) yields:

$$\frac{1}{U_o A_o} = \frac{1}{C_i \Omega A_i} + R_w + \frac{1}{\alpha Z A_o} \quad (4.21)$$

which can be written as:

$$\left[\frac{1}{U_o} - R_w A_o \right] \cdot Z = \frac{1}{C_i} \cdot \left[\frac{A_o Z}{\Omega A_i} \right] + \frac{1}{\alpha} \quad (4.22)$$

By letting:

$$Y = \left[\frac{1}{U_o} - R_w A_o \right] \cdot Z \quad (4.23)$$

$$X = \frac{A_o Z}{A_i \Omega} \quad (4.24)$$

$$m_1 = \frac{1}{C_i} \quad (4.25)$$

and:

$$b = \frac{1}{\alpha} \quad (4.26)$$

Equation (4.22) can be written in simple linear form as:

$$Y = m_1 X + b \quad (4.27)$$

Due to the temperature dependence of the parameters Ω and Z , the program utilizes an iterative procedure in the solution for each data point. A least-squares fit of equation (4.27) then determines C_i and α . To calculate h_o , the known value of

α can be used directly in equation (4.18); alternatively, with the known value of C_i , h_i can be calculated from equation (4.14), and applied to equation (4.9) in the following form:

$$h_o = \left[\frac{1}{U_o} - \left(\frac{A_o}{h_i A_i} + R_w A_o \right) \right]^{-1} \quad (4.28)$$

F. ENHANCEMENT RATIO

The enhancement ratios in this thesis are used to express a comparison of enhanced tube results to smooth tube results, or to compare wire-wrapped corrugated tube results to plain corrugated tube results.

From Nusselt's theory, heat flux can be written as:

$$q = a (T_{sat} - T_{wo})^{3/4} \quad (4.29)$$

where:

$$a = \alpha \left[\frac{k_f^3 g \rho_f^2 h_{fg}}{\mu_f D_o} \right]^{1/4} \quad (4.30)$$

Heat flux can also be represented by:

$$q = h_o (T_{sat} - T_{wo}) \quad (4.31)$$

Equating equations (4.29) and (4.31) yields:

$$h_o = a (T_{sat} - T_{wo})^{-1/4} \quad (4.32)$$

Taking the ratio of the outside heat transfer coefficient from an enhanced tube, (h_{oe}), to a smooth tube (h_{os}), for the same ($T_{sat} - T_{wo}$) yields:

$$\epsilon_T = \frac{h_{oe}}{h_{os}} = \frac{a_e}{a_s} = \frac{\alpha_e}{\alpha_s} \quad (4.33)$$

Similarly, the enhancement ratio for a wire-wrapped corrugated tube to a plain corrugated tube at the same ($T_{sat} - T_{wo}$) can be represented by:

$$\epsilon_{Tc} = \frac{h_{owc}}{h_{oc}} = \frac{a_{wc}}{a_c} = \frac{\alpha_{wc}}{\alpha_c} \quad (4.34)$$

where the subscripts wc and c refer to wire-wrapped corrugated and plain corrugated tubes respectively.

For the purpose of this study all enhancement results for wire-wrapped corrugated tubes are based on ϵ_{Tc} and wire-wrapped smooth tube enhancements are based on ϵ_T .

V. RESULTS AND DISCUSSION

A. HEAT TRANSFER CORRELATIONS

Lorenz et al. [Ref. 52] conducted a thorough investigation of several inside heat transfer correlations to determine which correlation most accurately predicted their data for turbulent flow of water in smooth tubes. Their findings showed that the Petukov-Popov and Sleicher-Rouse correlations (equations (2.24) and (2.21) respectively) were the most accurate in predicting the inside heat transfer coefficient over the range of Prandtl numbers from 6.0 to 11.6. Consequently, O'Keefe [Ref. 18] made a comparison of his results obtained using both correlations to process data, which was collected from the same experimental apparatus used in this study. His results showed good agreement between the outside coefficients obtained for smooth copper and smooth titanium tubes, when the two correlations were used with the modified Wilson plot data reduction technique. Based on his findings, O'Keefe [Ref. 18] processed most of his data using the Petukhov-Popov correlation. All data collected in this study were processed using the Petukov-Popov correlation so a direct comparison could be made with the results obtained by O'Keefe [Ref. 18].

The data collection and reduction program, DRPML, listed in Appendix C, allows for the selection from two possible outside heat transfer correlations, the Nusselt theory or the Fujii correlation (equations (2.1) and (2.6) respectively). Figure 5 shows the reduced results for h_0 obtained from using these two equations for a vacuum pressure run on a plain MHT Korodense tube. It can be seen that there is good agreement between the two equations. This indicates that the leading coefficient, α , obtained from the modified Wilson plot method using the Nusselt theory compensates for any vapor velocity effect inherent in the Fujii correlation. O'Keefe [Ref. 18] processed all of his data using the Nusselt correlation; so for comparison purposes, all further calculations of the outside heat transfer coefficient in the present work have also been made using the Nusselt theory.

B. VERIFICATION AND REPEATABILITY OF RESULTS

Several runs were made using the same tubes tested by previous researchers to verify system operation and data collection procedures. The five tubes that were tested included two smooth titanium tubes and two LPD Korodense titanium tubes tested by O'Keefe [Ref. 18]; of these, one of each was wrapped with a 0.5 mm diameter titanium wire. The fifth tube was a smooth copper tube wrapped with a 0.5 mm diameter titanium wire from Mitrou's work [Ref. 14]. Figures 6 and 7 are comparisons of the outside heat transfer

Ho vs. Tcf MHT Korodense Tube Under Vacuum

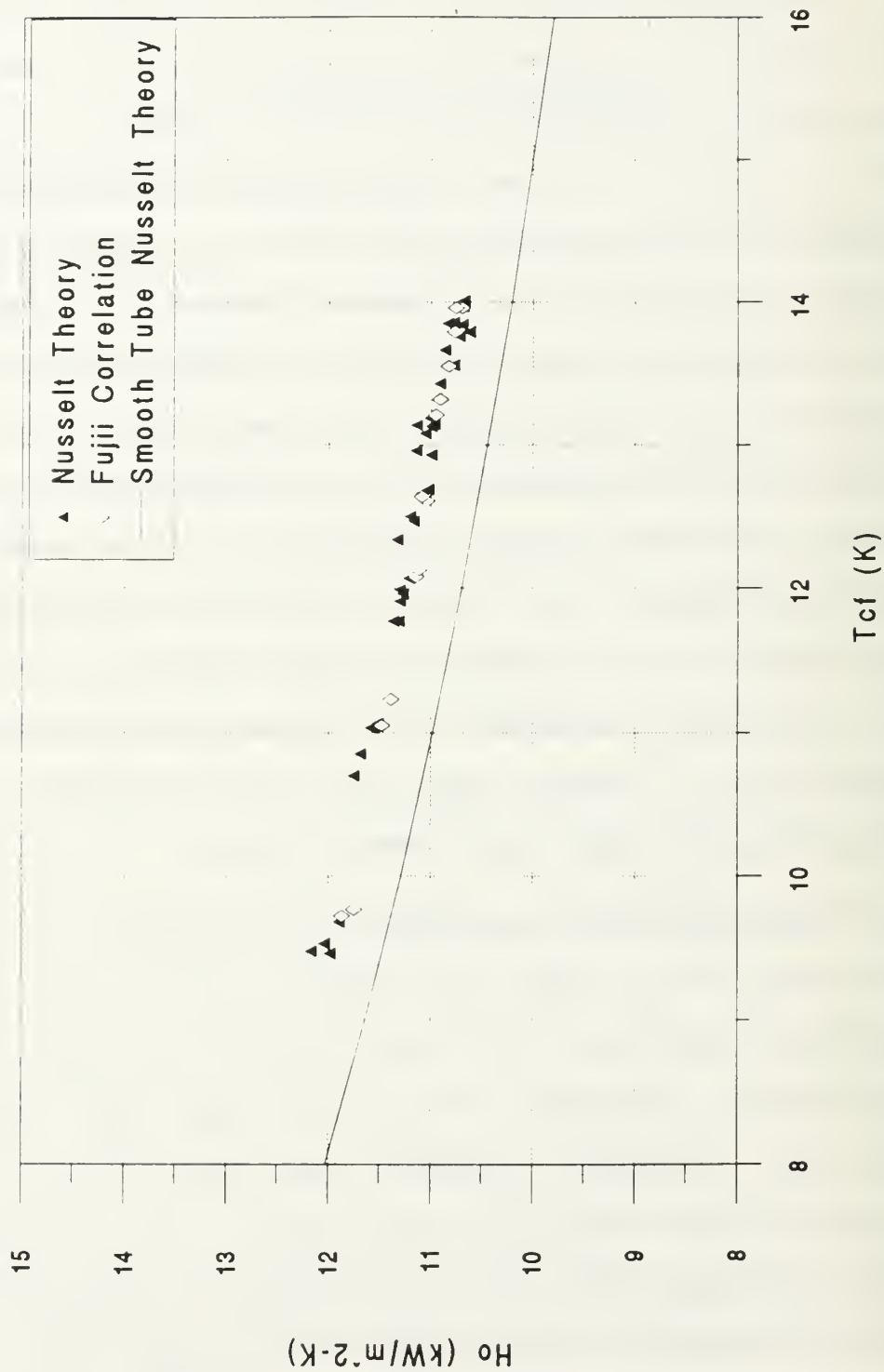


Figure 5. h_o vs. ΔT_{cf} for a Plain MHT Korodense Tube Under Vacuum

Ho vs. Tcf Smooth Titanium Tube Under Vacuum

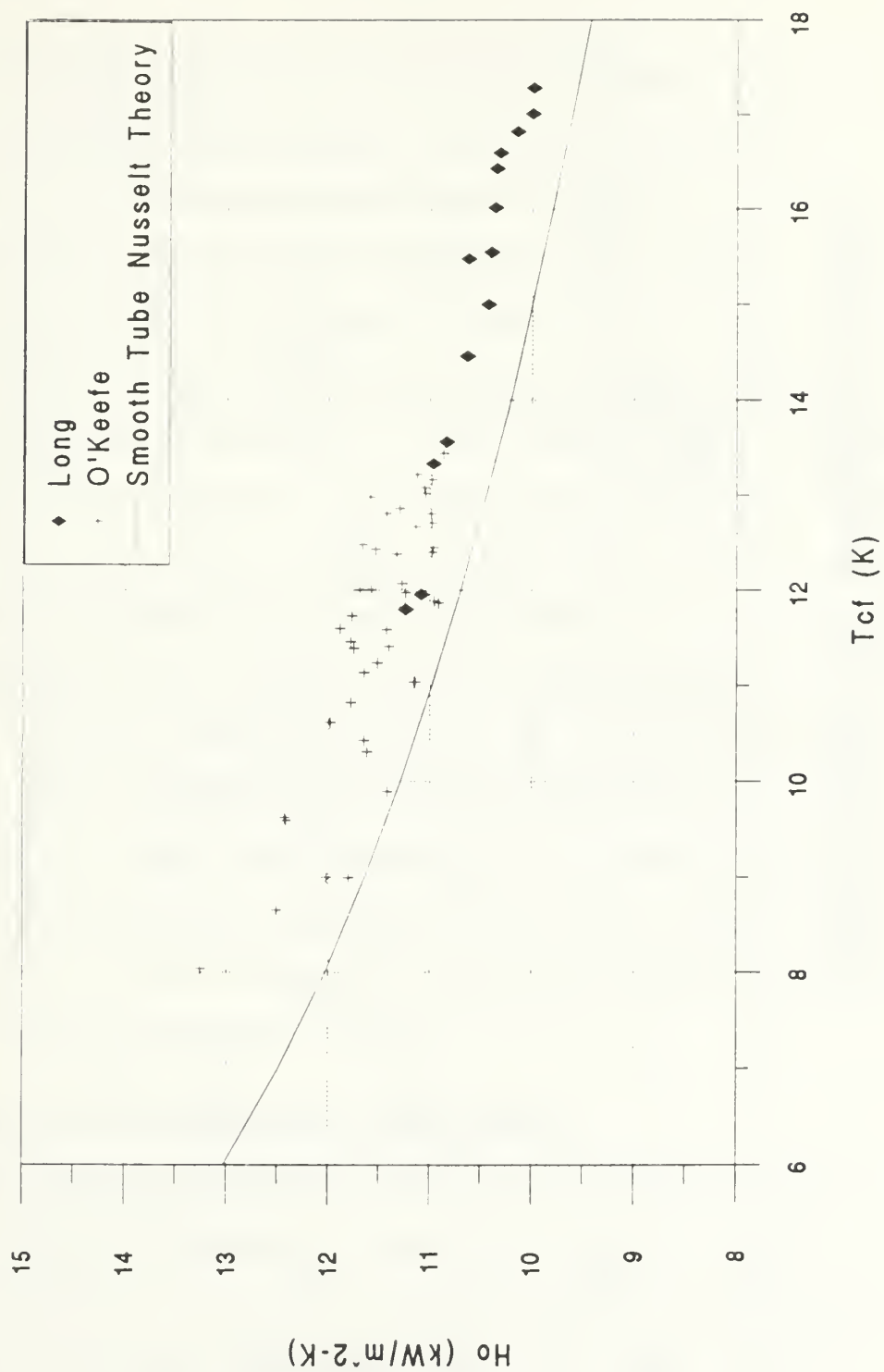


Figure 6. h_o vs. ΔT_{cf} for a Smooth Titanium Tube Under Vacuum

Smooth Titanium Tube Atmospheric Pressure h_o vs. T_{cf}

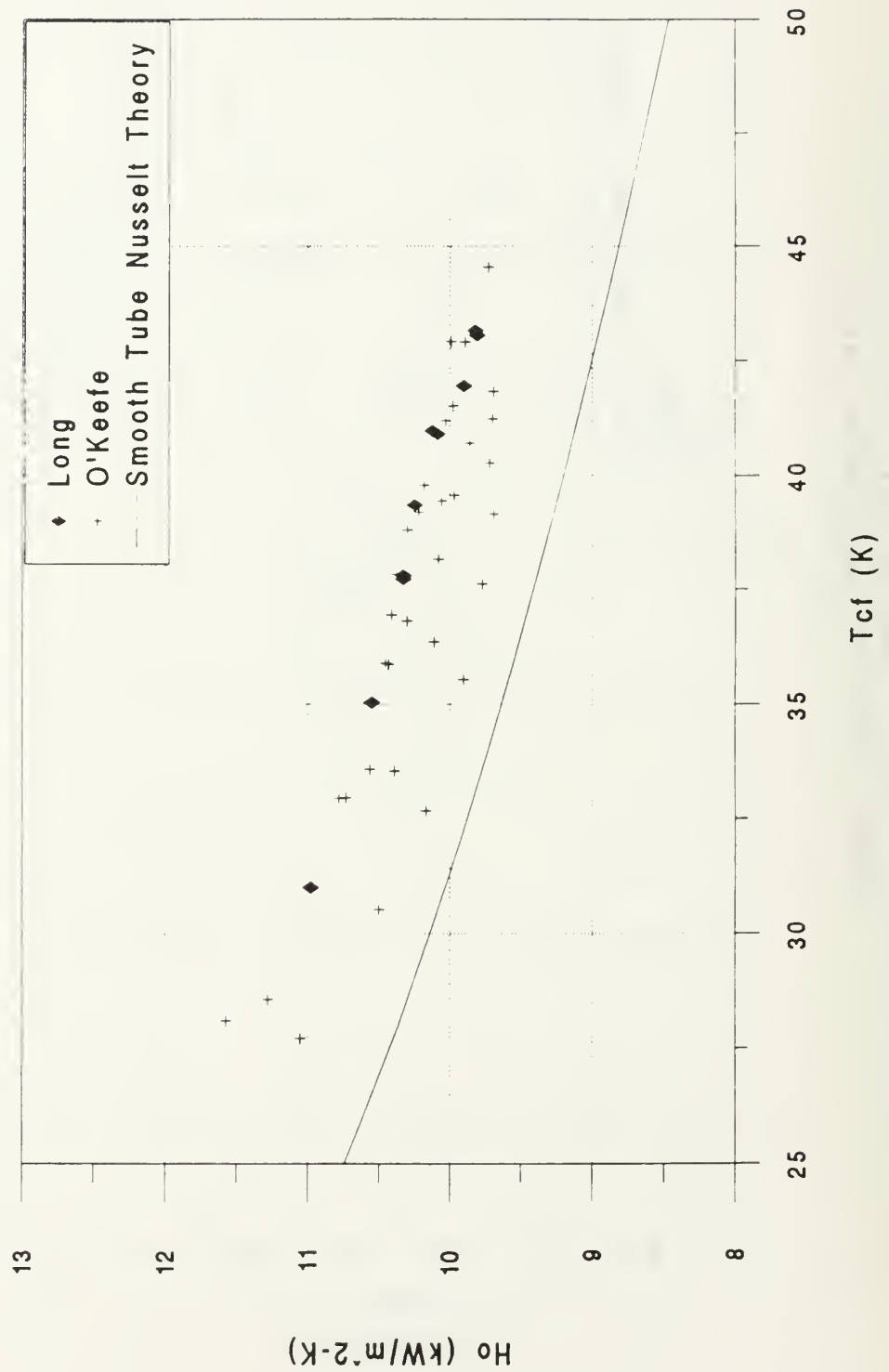


Figure 7. h_o vs. ΔT_{cf} for a Smooth Titanium Tube at Atmospheric Pressure

coefficient for a vacuum and an atmospheric pressure run respectively for data collected in this study and the study conducted by O'Keefe [Ref. 18] for the smooth titanium tube. The figures show good agreement for the two sets of data. The separation in the data sets seen in Figure 6 is due to a higher coolant water inlet temperature when O'Keefe conducted his runs. Tables II through VII contain a listing of all the data collected by O'Keefe, Mitrou and from the present study for comparison purposes in this study. The researcher initials are as follows: (O)=O'Keefe [Ref. 18], (L)=Long, and (M)=Mitrou [Ref. 14]. The average variation for α , the leading coefficient for the outside heat transfer equation, was less than 3.3%, with 90% of the results differing by less than 2%. The C_i values obtained in this study differed by as much as 8.5% compared with values obtained by previous researchers. This larger difference is possibly due to the uncertainty as to which HEATEX insert was used in O'Keefe's experiments. Four different inserts were available and each had a slightly different length.

C. ANALYSIS OF CORRUGATED TUBE RESULTS

To establish a base line for the enhancement ratios of the wire-wrapped MHT Korodense tubes, an initial series of runs were conducted to determine the heat transfer characteristics of the plain MHT Korodense tube. The data obtained are presented in Table VIII. Figure 8 shows a near unity

Table II. SMOOTH TITANIUM TUBE AT ATMOSPHERIC PRESSURE

HEATEX Insert		
Data Run/Researcher	C_i	α
FONMAHT1 (O)	2.38	0.75
FONMAHT2 (O)	2.38	0.77
FONMAHT3 (O)	2.39	0.76
FONMAHT4 (O)	2.41	0.75
FONMAHT5 (O)	2.20	0.77
FONMAHT6 (O)	2.54	0.76
FONMAHT7 (O)	2.51	0.75
LSNTHA1 (L)	2.90	0.75
No Insert		
FONMANT1 (O)	1.21	0.75
FONMANT2 (O)	1.18	0.76
FONMANT3 (O)	1.17	0.77
FONMANT4 (O)	1.18	0.76
FONMANT5 (O)	1.24	0.79
LSNTNA1 (L)	1.17	0.82

enhancement of the outside heat transfer coefficient for the MHT Korodense tube (having a groove pitch of 8 mm) over smooth titanium tube results. This is consistent with the findings of Rabas [Ref. 41] where, in a comparison of an extensive collection of data on spirally indented tubes he found:

... that there is no appreciable enhancement for condensation on roped tubes for groove pitches greater than 4 mm.

Table III. SMOOTH TITANIUM TUBE AT VACUUM PRESSURE

HEATEX Insert		
Data Run/Researcher	C_i	α
FONMVHT3 (O)	2.55	0.85
FONMVHT4 (O)	2.29	0.79
FONMVHT5 (O)	2.42	0.79
LSNTHV1 (L)	2.87	0.78
LSNTHV2 (L)	2.87	0.79
LSNTHV3 (L)	2.43	0.79
LSNTHV4 (L)	2.50	0.78
No Insert		
FONMVNT2 (O)	1.08	0.82
FONMVNT3 (O)	1.08	0.79
FONMVNT4 (O)	1.07	0.85
FONMVNT5 (O)	1.11	0.82
LSNTNV1 (L)	1.13	0.83
LSNTNV2 (L)	1.13	0.84
LSNTNV4 (L)	1.11	0.83

A comparison of the C_i values for the no insert runs on the smooth tube (Tables II and III) and LPD tube (Table V) indicate increases in h_i from 73 to 74% for vacuum and atmospheric pressure runs respectively. As discussed earlier, Wolverine [Ref. 2] reported a 25% increase in the inside heat transfer coefficient for the MHT Korodense tube when compared to the LPD Korodense tube. Comparison of the C_i values for the no insert runs on the MHT tube (Table VIII) and the LPD tube

Table IV. 0.5 mm WIRE-WRAPPED SMOOTH TITANIUM TUBE WITH HEATEX INSERT

Atmospheric Pressure		
Data Run/Researcher	C_i	α
FONMAH6T2 (O)	2.39	0.99
FONMAH5T3 (O)	2.37	1.01
LSW1THA1 (L)	2.67	1.04
Vacuum Pressure		
FONMVH6T1 (O)	2.16	0.95
FONMVH6T2 (O)	2.21	0.95
LSW1THV1 (L)	2.59	0.94

(Table V) indicate increases in h_i comparable to those reported by Wolverine [Ref. 2], 21% for the atmospheric pressure runs and 25% for the vacuum runs. This indicates that as the groove depth increases from the smooth tube (zero) to the LPD tube value (≈ 0.33 mm) most of the increase in the inside heat transfer coefficient due to corrugation has already been realized. The additional groove depth of the MHT tube provides only a 21 to 25% further increase of the inside heat transfer above the LPD results (MHT tube groove depth ≈ 0.5 mm), while the pressure drop doubles [Ref. 2].

Figures 9 and 10 show the effect of using the HEATEX insert on the overall heat transfer coefficient (U_0). The general trend for U_0 to increase with increasing coolant flow velocity is due to improved coolant mixing and a lower mean

Table V. PLAIN LPD KORODENSE TUBE

Atmospheric Pressure HEATEX Insert		
Data Run/Researcher	C_i	α
FONMAHLT2 (O)	2.90	0.90
FONMAHLT3 (O)	2.89	0.92
LLNTHA1 (L)	3.11	0.95
Atmospheric Pressure No Insert		
FONMANLT2 (O)	2.06	0.92
FONMANLT3 (O)	1.99	0.94
LLNTNA2 (L)	2.17	0.95
Vacuum Pressure HEATEX Insert		
FONMVHLT1 (O)	2.72	0.94
FONMVHLT2 (O)	2.67	0.95
LLNTHV2 (L)	3.02	0.97
Vacuum Pressure No Insert		
FONMVNLT2 (O)	1.87	0.95
FONMVNLT3 (O)	1.86	0.96
LLNTNV3 (L)	1.99	0.96

bulk fluid temperature. Increases range from 3% at a coolant flow rate of 3.83 m/s up to 9% at a flow rate of 1.02 m/s. This increase is attributed to the greater turbulence of the coolant flow due to the presence of the insert and can be seen in the higher C_i values for the HEATEX runs for every tube tested. A comparison of O'Keefe's data [Ref. 18] for smooth titanium and LPD Korodense titanium tubes, tested with and

Table VI. 0.5 mm WIRE-WRAPPED LPD KORODENSE TUBE WITH HEATEX INSERT

Atmospheric Pressure		
Data Run/Researcher	C_i	α
FONMAHL3T3 (O)	2.84	0.97
LLW05THA1 (L)	3.03	0.98
LLW05THA2 (L)	3.06	0.98
Vacuum Pressure		
FONMVHL3T1 (O)	2.61	0.99
LLW05THV1 (L)	2.78	0.98
LLW05THV2 (L)	2.78	0.98

without a HEATEX insert indicates a 20% increase in U_0 for the smooth tube and a 7.9% increase in U_0 for the LPD tube when tested at a coolant velocity of ≈ 2.5 m/s. For a coolant flow rate of ≈ 2.5 m/s the present study shows a 7.2% increase in U_0 for the MHT tube when a HEATEX insert is used. This trend indicates that a more severe corrugation groove depth (zero for the smooth tube, 0.33 mm for the LPD tube and 0.5 mm for the MHT tube) results in a smaller increase in U_0 with the addition of an insert. The grooves present in the MHT and LPD tubes cause greater turbulence in the coolant flow than the inside walls of the smooth tube. Therefore, the addition of an insert for a corrugated tube (which already has turbulent flow) has a less pronounced effect on U_0 compared to the effect realized for a smooth tube.

Table VII. 0.5 mm WIRE-WRAPPED SMOOTH COPPER TUBE WITH HEATEX INSERT

Atmospheric Pressure		
Data Run/Researcher	C_i	α
FONMAH71C1 (O)	3.07	1.50
LSW71CHA1 (L)	3.15	1.28
S71A305* (M)	2.69	1.50
S71A314* (M)	2.69	1.50
Vacuum Pressure		
FONMVH71C2 (O)	2.76	1.28
LSW71CHV1 (L)	2.94	1.23
S71V296* (M)	2.50	1.27

* Runs conducted with wire-wrapped insert

D. ANALYSIS OF WIRE-WRAPPED CORRUGATED TUBE RESULTS

Seven different titanium wire diameters ranging from 0.1 mm to 1.6 mm were used to wrap separate MHT Korodense tubes. Tests were conducted at atmospheric and vacuum conditions and the results were compared to the plain MHT Korodense tube data to determine the enhancement effects attributable to wire-wrapping. Wire-wrapped smooth tube data obtained by previous researchers were also used for comparison to establish if similar trends exist.

The enhancement due to wire-wrapping can be seen directly in Figure 11 where the averaged U_0 (averaged for all data runs at each flow rate) are plotted for all the wire diameters.

Table VIII. PLAIN MHT KORODENSE TUBE

Atmospheric Pressure HEATEX Insert		
Data Run	C_i	α
LMNTHA7	3.34	0.79
LMNTHA8	3.31	0.79
LMNTHA9	3.32	0.80
Atmospheric Pressure No Insert		
LMNTNA7	2.49	0.80
LMNTNA8	2.47	0.80
LMNTNA9	2.56	0.80
Vacuum Pressure HEATEX Insert		
LMNTHV7	3.07	0.78
LMNTHV8	3.01	0.79
LMNTHV9	3.06	0.78
Vacuum Pressure No Insert		
LMNTNV7	2.36	0.77
LMNTNV8	2.39	0.76
LMNTNV9	2.43	0.77

Here the 0.4 mm wire-wrap appears to give the best heat transfer with an enhancement of about 3%. Similar trends for the outside heat transfer coefficient can also be seen in Figures 12 and 13. The plain MHT Korodense tube results are included to show the relative enhancements for each size of wire. Figure 12 shows an increasing trend with decrease in wire diameter starting from the 1.6 mm wire-wrap ($P_w/D_w=5$) and

Ho vs. Tcf MHT Korodense Tube and Smooth Titanium Tube Under Vacuum

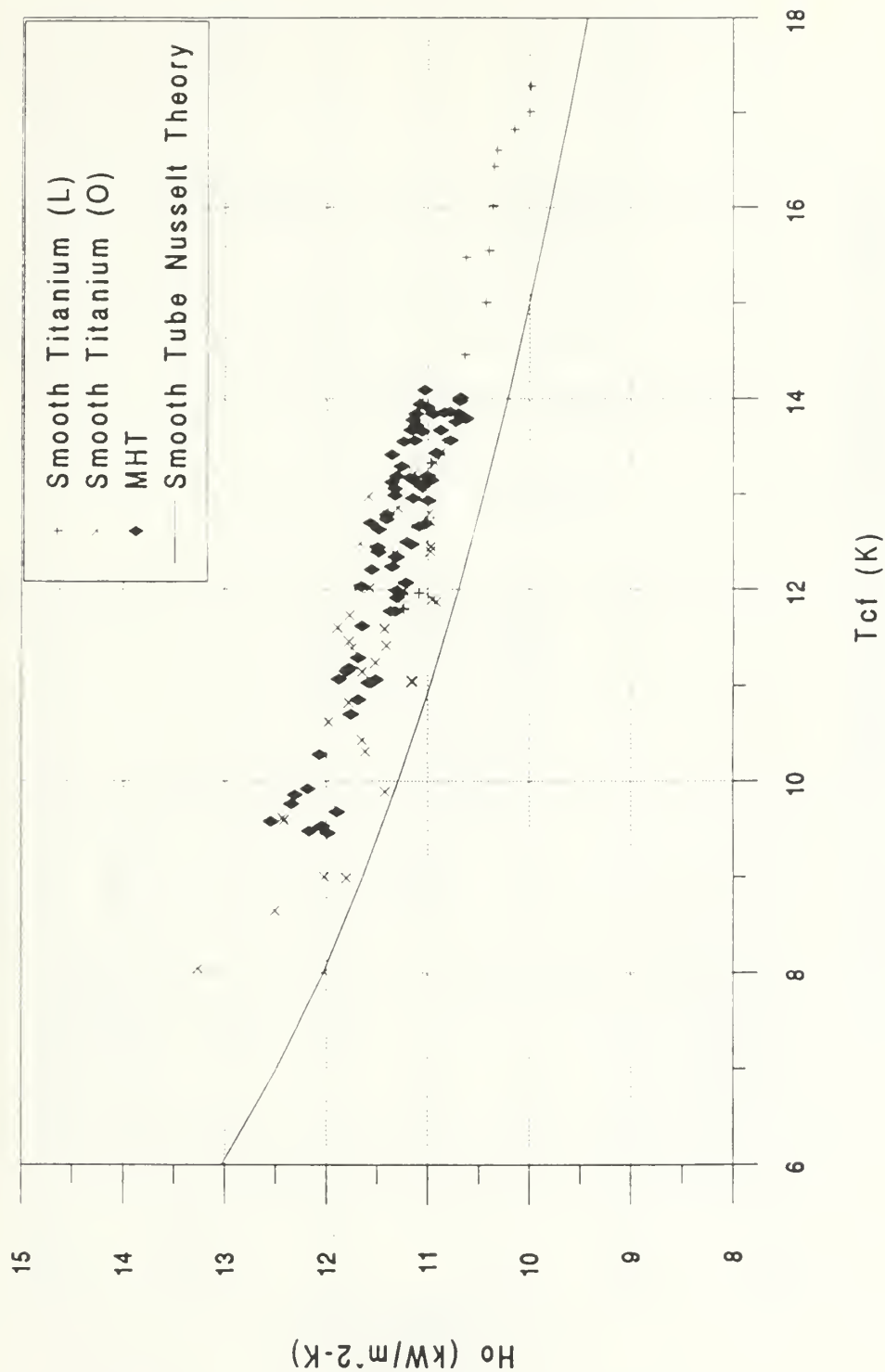


Figure 8. h_o vs. ΔT_{cf} for a Smooth Titanium and a Plain MHT Korodense Tubes Under Vacuum

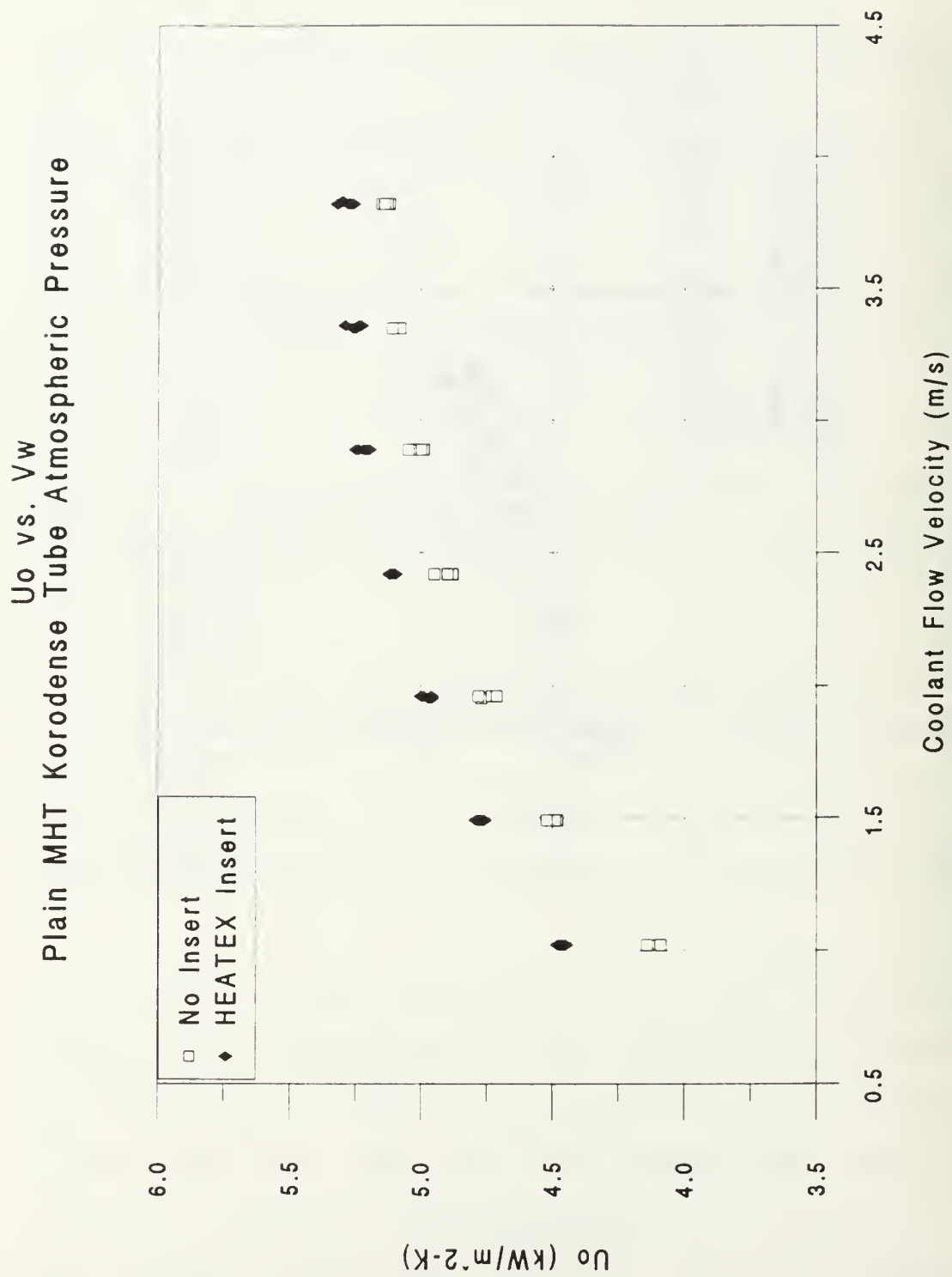


Figure 9. U_o vs. V_w for a Plain MHT Korodense Tube at Atmospheric Pressure

U_o vs. V_w
Plain MHT Korodense Tube Under Vacuum

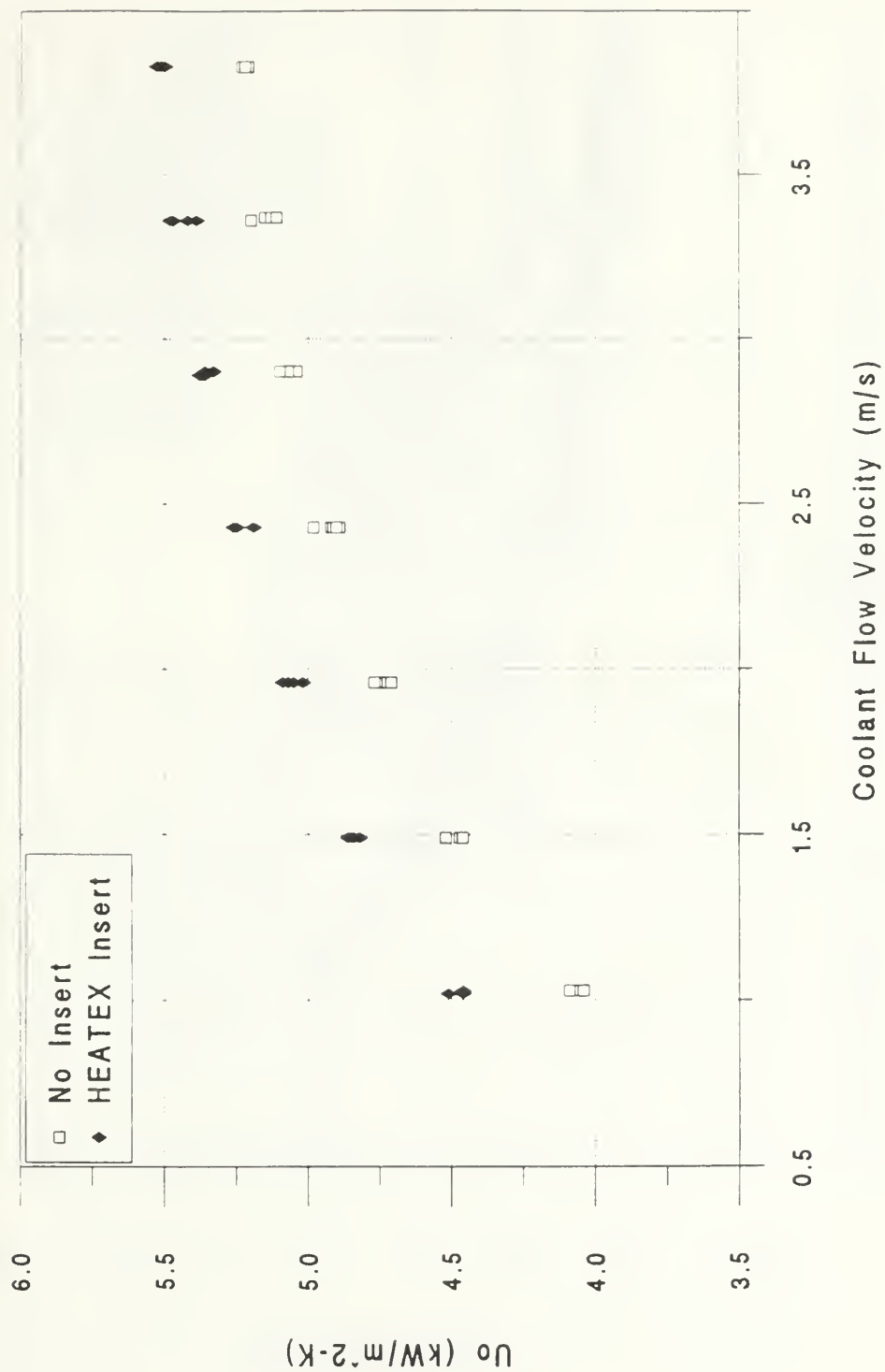


Figure 10. U_o vs. V_w for a Plain MHT Korodense Tube Under Vacuum

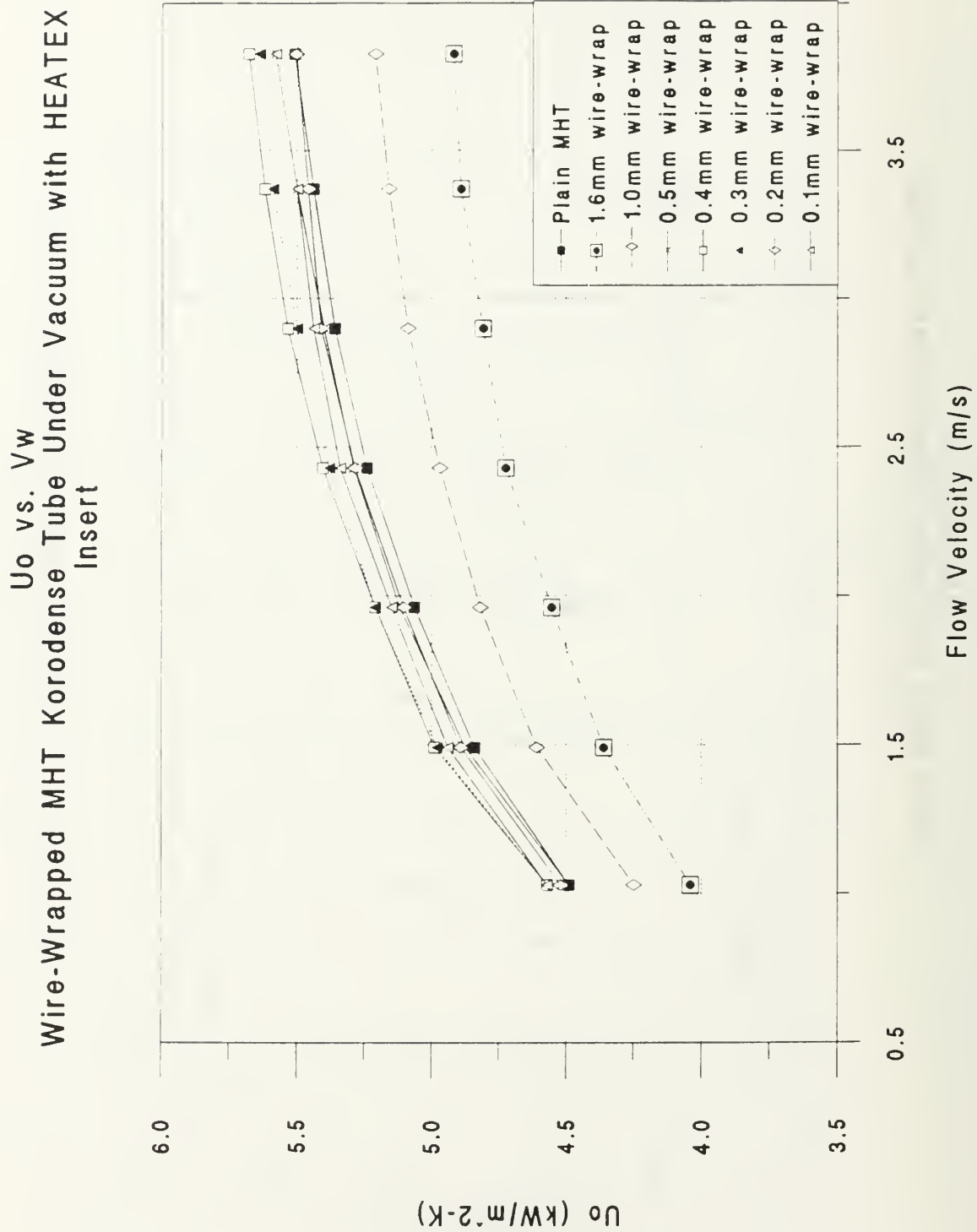


Figure 11. U_o vs. V_w for Wire-Wrapped MHT Korodense Tubes Under Vacuum with HEATEX Insert

Ho vs. Tcf Under Vacuum

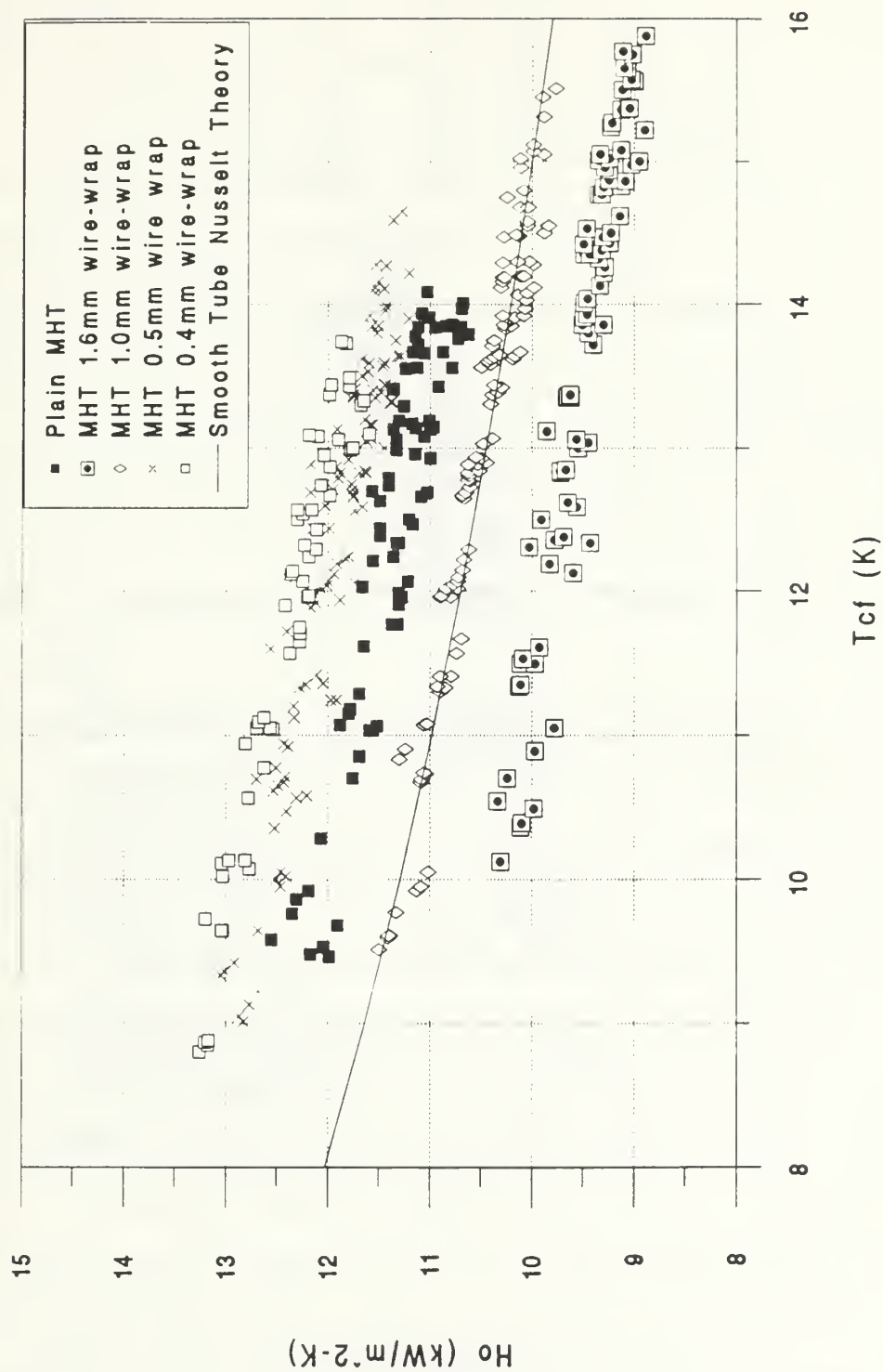


Figure 12. h_o vs. T_{cf} for Wire-Wrapped MHT Korodense Tubes Under Vacuum

Ho vs. Tcf Under Vacuum

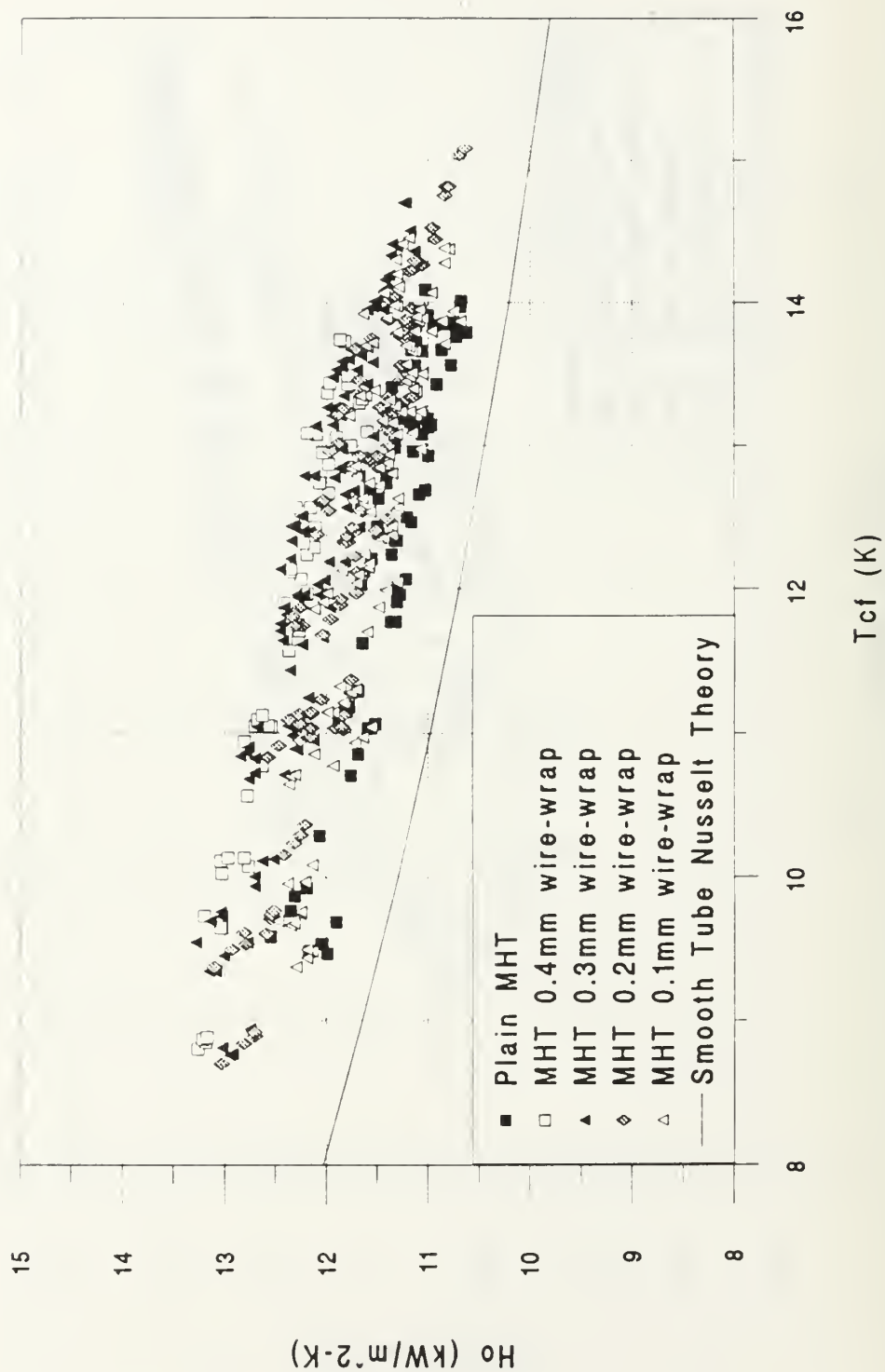


Figure 13. h_o vs. T_{cf} for Wire-Wrapped MHT Korodense Tubes Under Vacuum

an enhancement ratio of 0.88 to the 0.4 mm wire-wrap ($P_w/D_w=20$) with an enhancement ratio of 1.08. Figure 13 completes the data and shows the trend returning to the plain MHT tube results, starting with the 0.4 mm wire-wrap and ending with the 0.1 mm wire-wrap ($P_w/D_w=80$). Two separate figures were used to help eliminate the clutter from the overlapping data. Table IX contains the averaged C_i and α values for all the conditions tested (vacuum and atmospheric pressure, with and without the HEATEX insert) for the plain MHT tube and all the wire-wrapped MHT tubes. Two to four tests were conducted at each condition to ensure repeatability of the data.

The wire-wrapped MHT tube data were also checked to see if there was a relationship between the fractional coverage and the pitch to wire diameter ratio to the enhancement over the plain MHT tube (E_{TC}). Figure 14 shows the relationship between the enhancement ratio and the pitch to wire diameter ratio and Figure 15 shows enhancement ratio versus fractional coverage. Data obtained by O'Keefe [Ref. 18] for wire-wrapped LPD Korodense tubes are also included in the figures. However, the number of his tests are limited to only 3 wire diameters (0.5mm, 1.0mm and 1.6mm). The data clearly indicate that wrapping with a large diameter wire causes a degradation in performance. As the wire diameter is decreased, the enhancement passes through a maximum of about 8%, corresponding to a $P_w/D_w \approx 20$ and a fractional coverage of $\approx 5\%$.

Table IX. WIRE-WRAPPED AND PLAIN MHT KORODENSE TUBES

Atmospheric Pressure				
Tube	No Insert		Heatex Insert	
	C_i	α	C_i	α
Plain	2.51	0.82	3.32	0.79
1.6mm wire-wrap	2.31	0.72	2.92	0.73
1.0mm wire-wrap	2.35	0.78	3.27	0.79
0.5mm wire-wrap	2.50	0.85	3.19	0.85
1.0mm wire-wrap	2.53	0.84	3.38	0.85
0.3mm wire-wrap	2.52	0.84	3.27	0.85
1.0mm wire-wrap	2.53	0.82	3.38	0.82
0.4mm wire-wrap	2.50	0.81	3.36	0.82
Vacuum Pressure				
Plain	2.99	0.77	3.05	0.79
1.6mm wire-wrap	2.17	0.67	2.84	0.69
1.0mm wire-wrap	2.20	0.82	2.99	0.73
0.5mm wire-wrap	2.84	0.82	3.05	0.81
0.4mm wire-wrap	2.31	0.83	3.03	0.84
0.3mm wire-wrap	2.31	0.82	3.14	0.73
0.2mm wire-wrap	2.39	0.81	3.16	0.80
0.1mm wire-wrap	2.42	0.78	3.23	0.80

As the wire diameter is further decreased, the enhancement ratio returns to unity, i.e. back to the plain tube performance. The results from O'Keefe [Ref. 18] for the LPD Korodense tube definitely show the same trends as the MHT tube, but the results are somewhat inconclusive due to lack of

Enhancement Ratio vs. Pitch to Diameter Ratio
Wire-Wrapped MHT and LPD Korodense Tubes

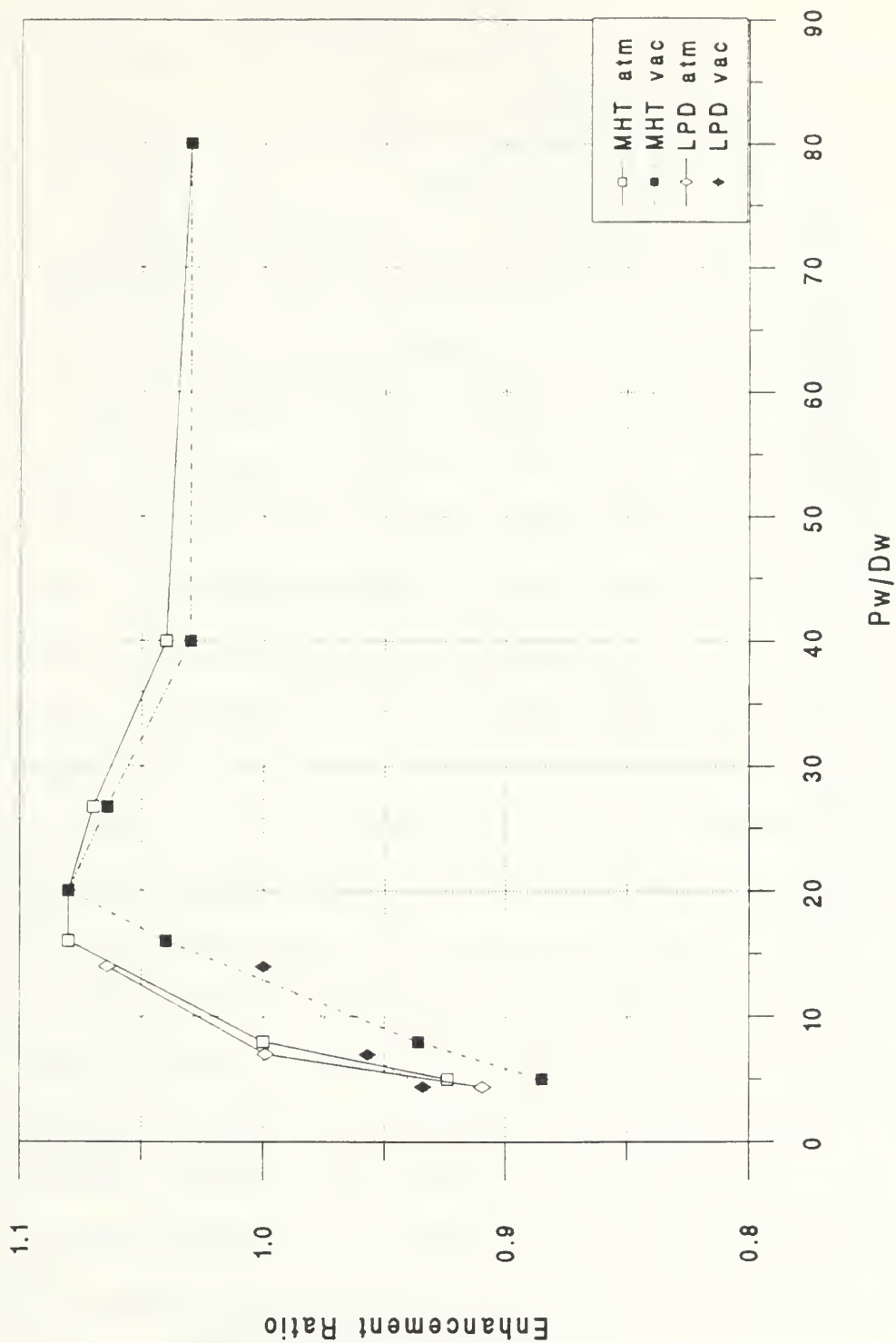


Figure 14. Enhancement Ratio vs. P_w/D_w for Wire-Wrapped Korodense Tubes

Enhancement vs. Fractional Coverage Wire-Wrapped MHT and LPD Korodense Tubes

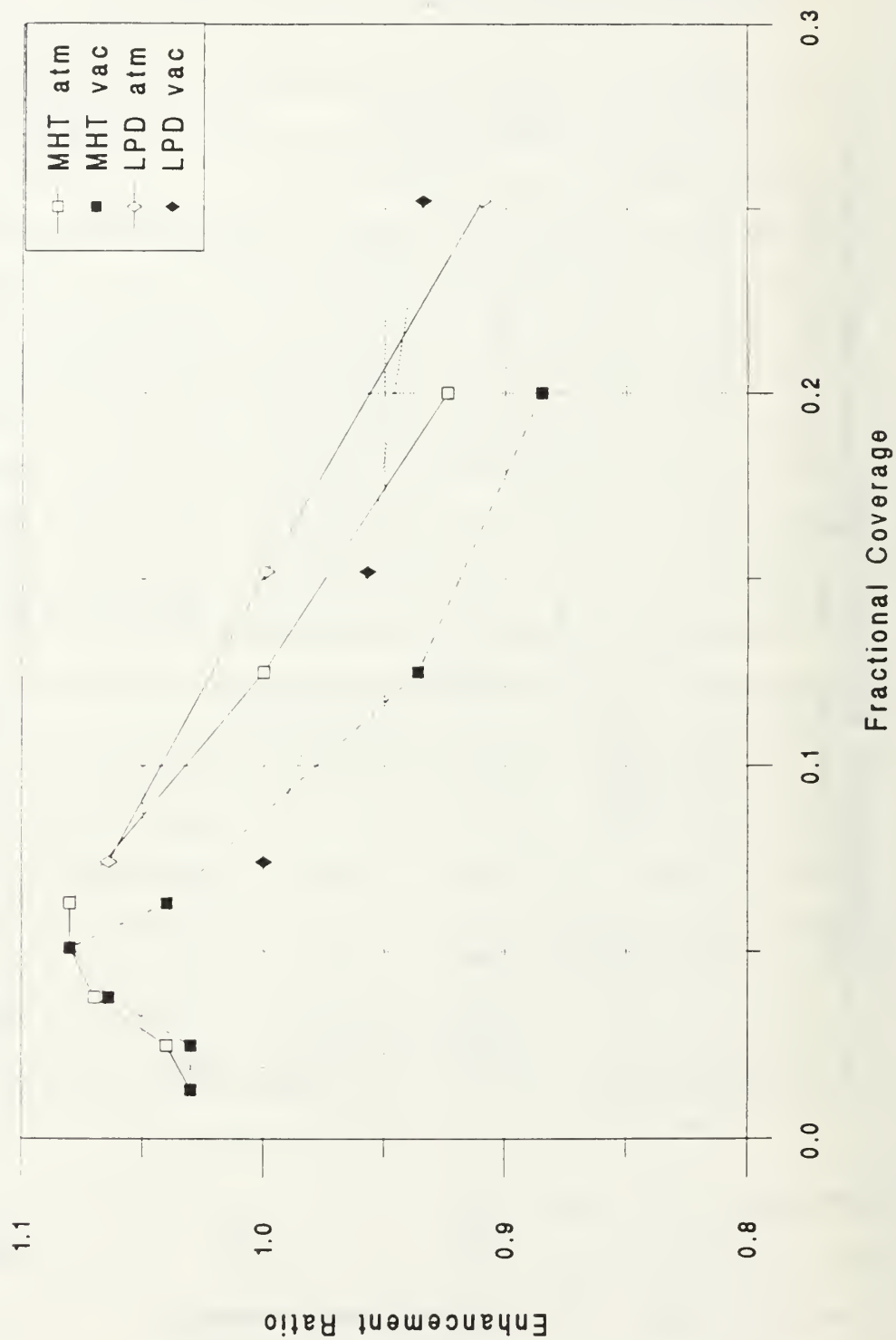


Figure 15. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense Tubes

data. His smallest wire diameter was only 0.5 mm.

The enhancement results obtained for the wire-wrapped MHT Korodense tube were also compared to a wire-wrapped smooth tube. Marto et al. [Ref. 31] reported an optimum wire pitch to diameter ratio ranging from 5 to 7 for wire-wrapped copper tubes. Sethumadhavan and Rao [Ref. 34] realized a maximum enhancement at a fractional coverage of 21%, corresponding to a $P_w/D_w \approx 5$. This value for P_w/D_w is much smaller than the optimum pitch to diameter ratio of 20 obtained in this study.

To further understand this relationship, data were compiled for wire-wrapped smooth tubes studied at NPS and compared with the current data in Figures 16 and 17. Both sets of data were plotted with constant pitch curves for a better comparison with the constant pitch results of the corrugated tubes. It can be seen that the wire-wrapped smooth copper and wire-wrapped smooth titanium tubes with $P_w = 4$ mm have roughly the same slope. The same trend can be seen for the wire-wrapped smooth titanium and the wire-wrapped LPD and MHT tubes with a pitch of about 7 mm. Due to the limited data it is difficult to predict the optimal fractional coverage of the wire-wrapped smooth tubes for a constant wire pitch. However, it does appear to be less than the 21% obtained by Sethumadhavan and Rao [Ref. 34]. It can also be seen that the magnitude of the enhancements tend to vary with tube material and tube geometry. Mitrou's data [Ref. 14] for wire-wrapped smooth copper tubes show results 45 to 55% higher than the

Enhancement Ratio vs. Pitch to Diameter Ratio
Wire-Wrapped Smooth and Korodense Tubes

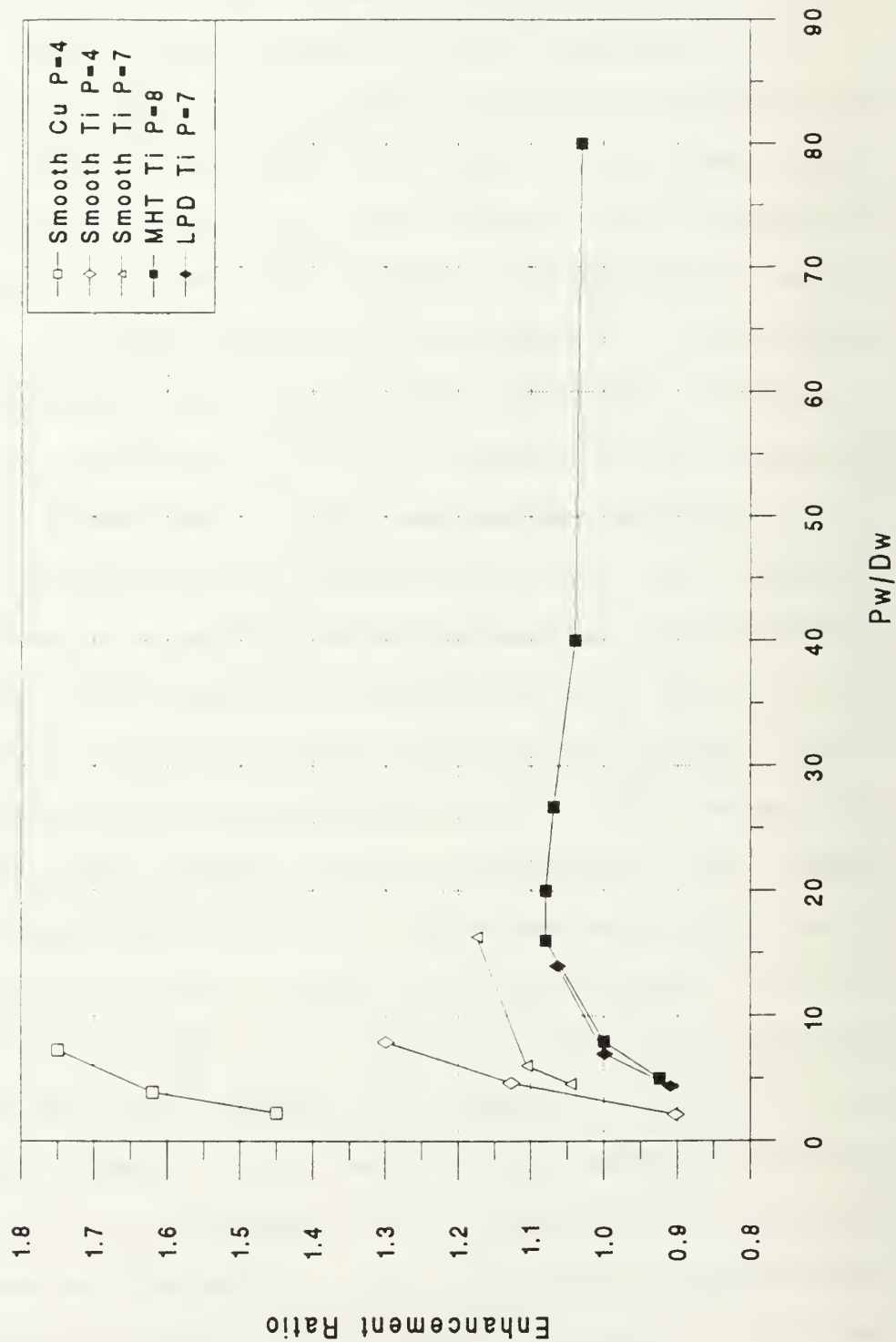


Figure 16. Enhancement Ratio vs. P_w/D_w for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes, NPS Data

Enhancement Ratio vs. Fractional Coverage
Wire-Wrapped Smooth and Korodense Tubes

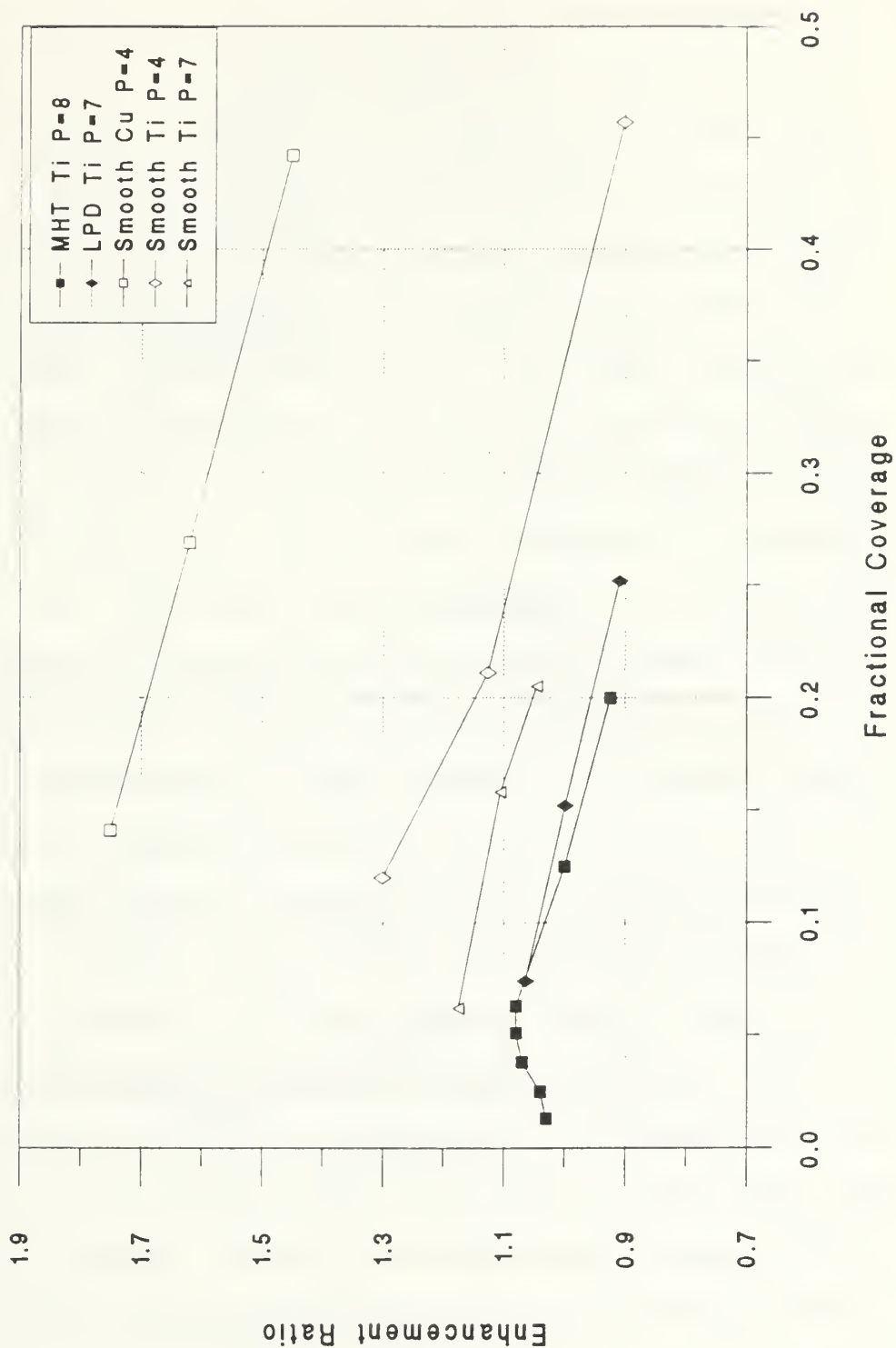


Figure 17. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes, NPS Data

wire-wrapped smooth titanium tube results for an equal pitch ($P_w=4$ mm) obtained by O'Keefe [Ref. 18]. This indicates that tubes made of materials with high thermal conductivities (such as copper) may provide additional enhancement characteristics. The effect of tube geometry can also be seen in the comparison of the wire-wrapped smooth titanium tube and the wire-wrapped LPD and MHT tubes (all with pitches ≈ 7 mm). The wire-wrapped smooth titanium tube achieved an enhancement $\approx 10\%$ higher than the corrugated tubes of similar pitch. Figures 18 and 19 are identical to Figures 16 and 17 with the addition of the data obtained by Sethumadhavan and Rao [Ref. 34]. The tube material used in their tests is not known, but appears to have a thermal conductivity between copper and titanium (such as copper/nickel or aluminum). The most noticeable differences in their data and the data from research at NPS are the fractional coverage of the apparent maximum enhancement and the opposite slope of the constant pitch curves. This is most likely due the wire material used for wrapping their tubes. They used copper wire and all the NPS tubes were manufactured with titanium wire. The use of a highly conductive material may have produced more of a 'fin' effect with the wire and caused the peak enhancement to shift. Further study on the effect of the wire material is required to determine the effects.

Possible effects on the inside heat transfer coefficient due to wire-wrapping both smooth and corrugated tubes were

Enhancement Ratio vs. Pitch to Diameter Ratio Wire-Wrapped Smooth and Korodense Tubes

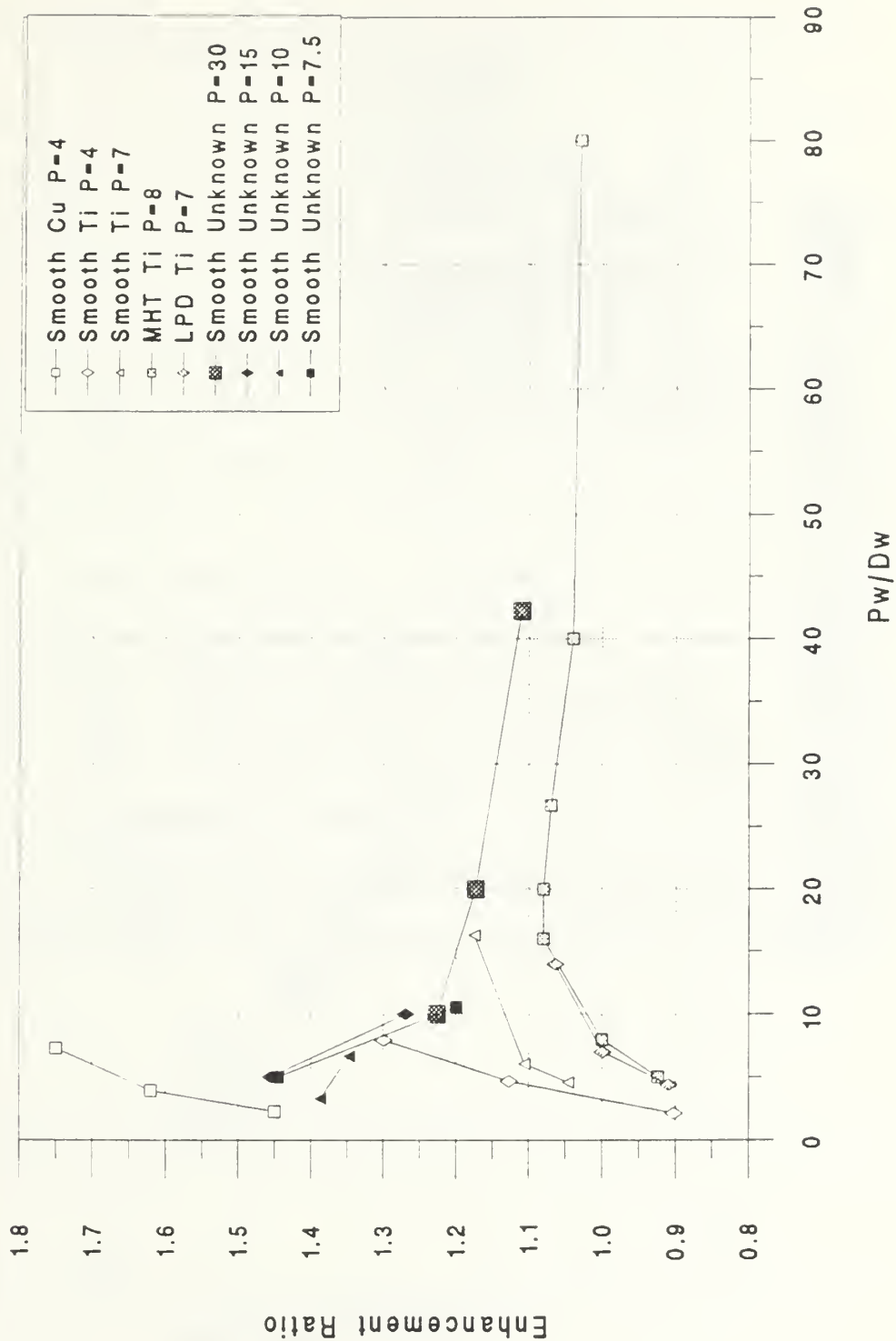


Figure 18. Enhancement Ratio vs. P_w/D_w for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes

Enhancement Ratio vs. Fractional Coverage
Wire-Wrapped Smooth and Korodense Tubes

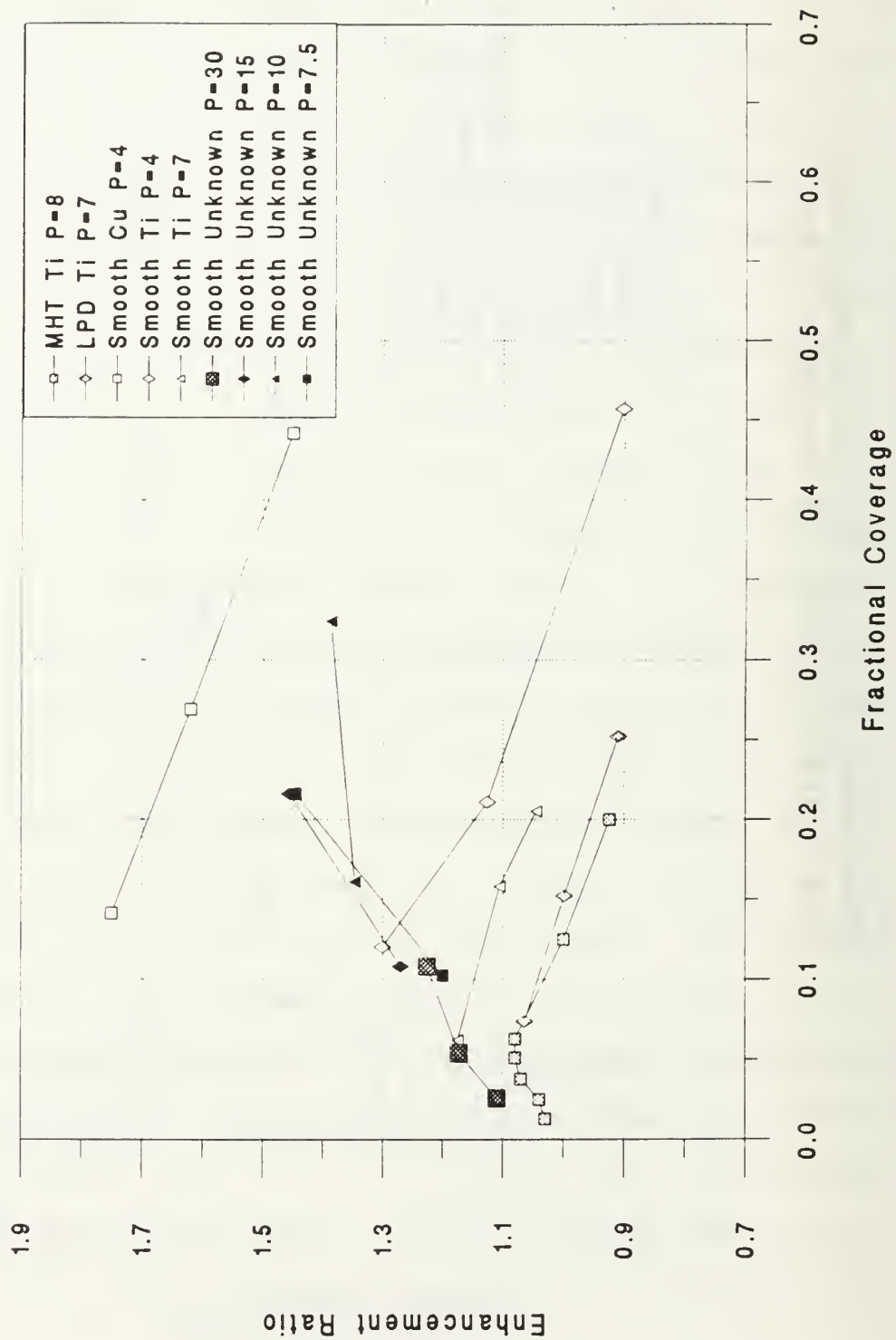


Figure 19. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes

also investigated. Figure 20 shows a possible decreasing trend in C_i with increasing fractional coverage. However, the magnitude of the decrease is minimal and the overall variation in C_i is within the uncertainty of the plain tube results.

In summary, the enhancement of the outside heat transfer coefficient for a titanium MHT Korodense tube over a smooth titanium tube was close to unity. The primary enhancement in the overall heat transfer coefficient was found to be due to an increase in the inside heat transfer coefficient, 21 to 26% above the LPD Korodense tube coefficient and 110 to 117% above the smooth tube coefficient. The effect of wire-wrapping corrugated tubes provides minimal additional enhancement to the outside heat transfer coefficient, a maximum of $\approx 8\%$ with a $P_w/D_w \approx 20$ and a corresponding fractional coverage of 5%. However, the addition of wire-wrap into the grooves of a corrugated tube may have greater benefit when used in a tube bundle arrangement due to improved condensate drainage.

Ci vs. Fractional Coverage

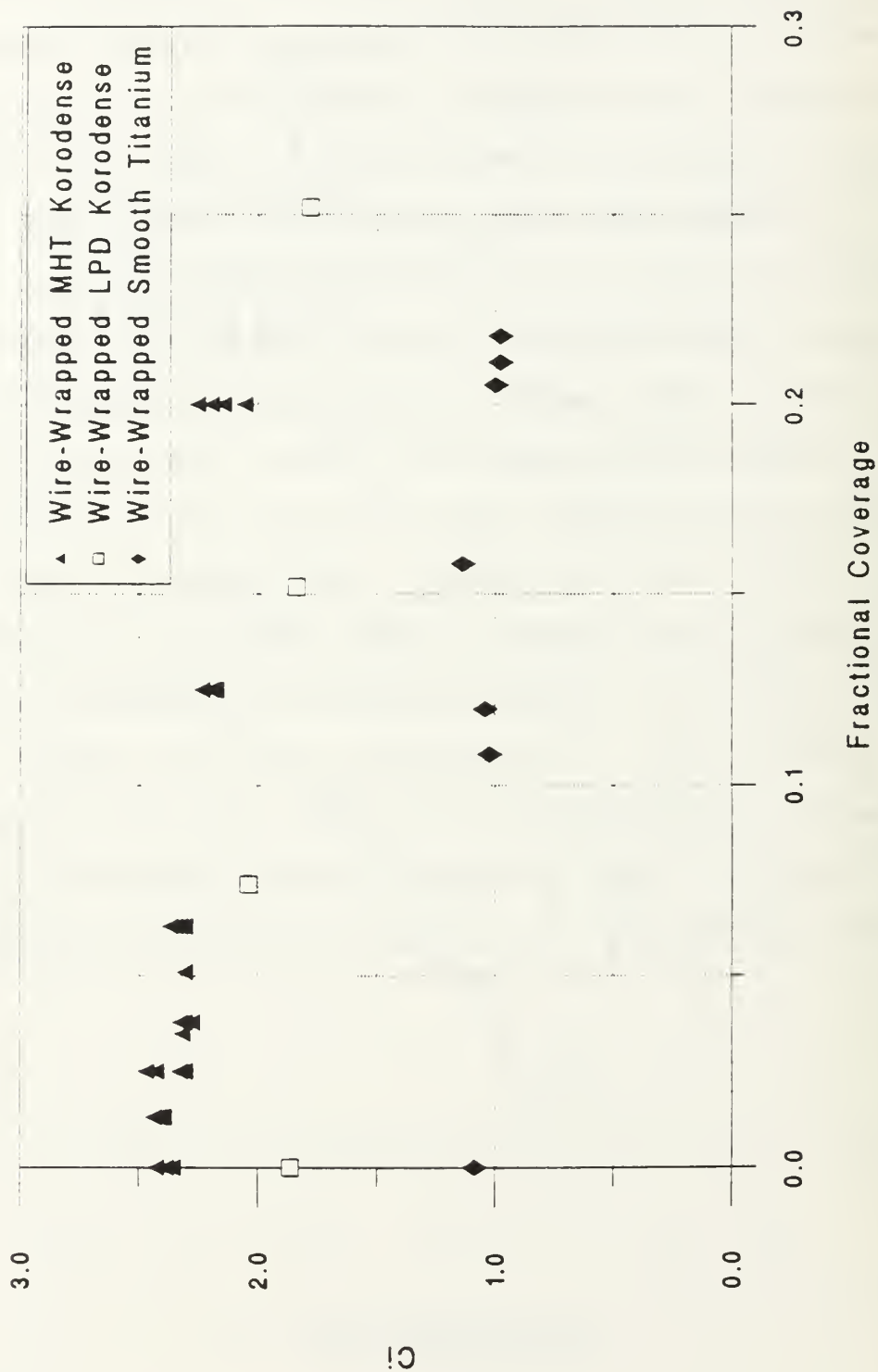


Figure 20. C_i vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes at Atmospheric Pressure

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Enhancement of the outside heat transfer coefficient due to the corrugation of the MHT Korodense titanium tube is near unity when compared to smooth tube results.
2. The corrugation of the MHT Korodense tube produces enhancements in the inside heat transfer coefficient from 110% to 117% above smooth tube results, and 21% to 26% above LPD Korodense tube results.
3. Wire-wrapping of MHT Korodense tubes yields minimal additional enhancement, $\approx 8\%$, when used in a single tube arrangement.
4. The optimal fractional coverage for the wire-wrapping of MHT Korodense tubes is $\approx 5\%$ ($P_w/D_w \approx 20$) when used in a single tube arrangement.
5. The thermal conductivity of the tube material effects the enhancement characteristics of wire-wrapped tubes.
6. Some relationship appears to exist between fractional coverage and the inside heat transfer coefficient.
7. The modified Wilson plot data reduction technique compensates for vapor velocity effects when using the Nusselt theory in determining the outside heat transfer coefficient.

B. RECOMMENDATIONS

1. Manufacture and test additional wire-wrapped LPD Korodense tubes with smaller wire diameters ranging from 0.1 mm to 0.4 mm to validate the trends found for the MHT Korodense tube.
2. Manufacture and test additional constant pitch wire-wrapped copper smooth tubes with wire diameters greater than 1.6 mm and less than 0.5 mm and determine the optimal wire diameter for specific wire pitches.
3. Test a set of wire-wrapped corrugated copper or copper/nickel tubes to determine the possible effect of

tube material on condensation, when compared to the titanium corrugated tubes.

4. Develop a numerical model to approximate the outside heat transfer characteristics for corrugated and wire-wrapped corrugated tubes.
5. Fabricate a set of corrugated tubes with outside electrical heater elements and conduct tests to validate the accuracy of the inside heat transfer correlations available for processing data on corrugated tubes with and without a HEATEX insert.
6. Input the Wolverine inside heat transfer correlation to the existing program. Reprocess selected corrugation tube data and compare results with those obtained by the Petukhov-Popov correlation.
7. Test wire-wrapped corrugated tubes in a tube bundle arrangement. Determine if additional overall bundle enhancement is possible with inundation effects included, and if the optimal fractional coverage shifts from that found for single tube tests.
8. Fabricate and test a set of multistart corrugated tubes with and without wire-wrapping to determine if additional enhancements can be realized using the multistart corrugation geometry.
9. Conduct additional tests on wire-wrapped smooth and corrugated tubes to determine if a relationship exists between fractional coverage and the inside heat transfer coefficient.
10. Test the enhancement effects of various wire materials when used for wire-wrapping smooth and corrugated tubes.
11. Investigate the possibility of bonding the wire-wrap to the tube surface and test the enhancement effects for smooth and corrugated tubes.

APPENDIX A. SYSTEM CORRECTIONS

A. FRICTIONAL TEMPERATURE CORRECTIONS

Coolant flowing through a tube experiences a temperature increase due to frictional heating. The magnitude of the temperature rise depends on the internal tube geometry and the velocity of the coolant. With the cooling water sump and the test section at ambient temperature, measurements were taken to determine the temperature increase due to frictional effects at flow rates ranging from 10% to 100% on the rotameter. Two separate runs were conducted for the MHT Korodense tube, one with the HEATEX insert installed and the second with no insert. Figure A. 1 show the results for the two runs. The data was curve fitted to a third order polynomial as shown in Table A. 1.

MHT Korodense Titanium Tube

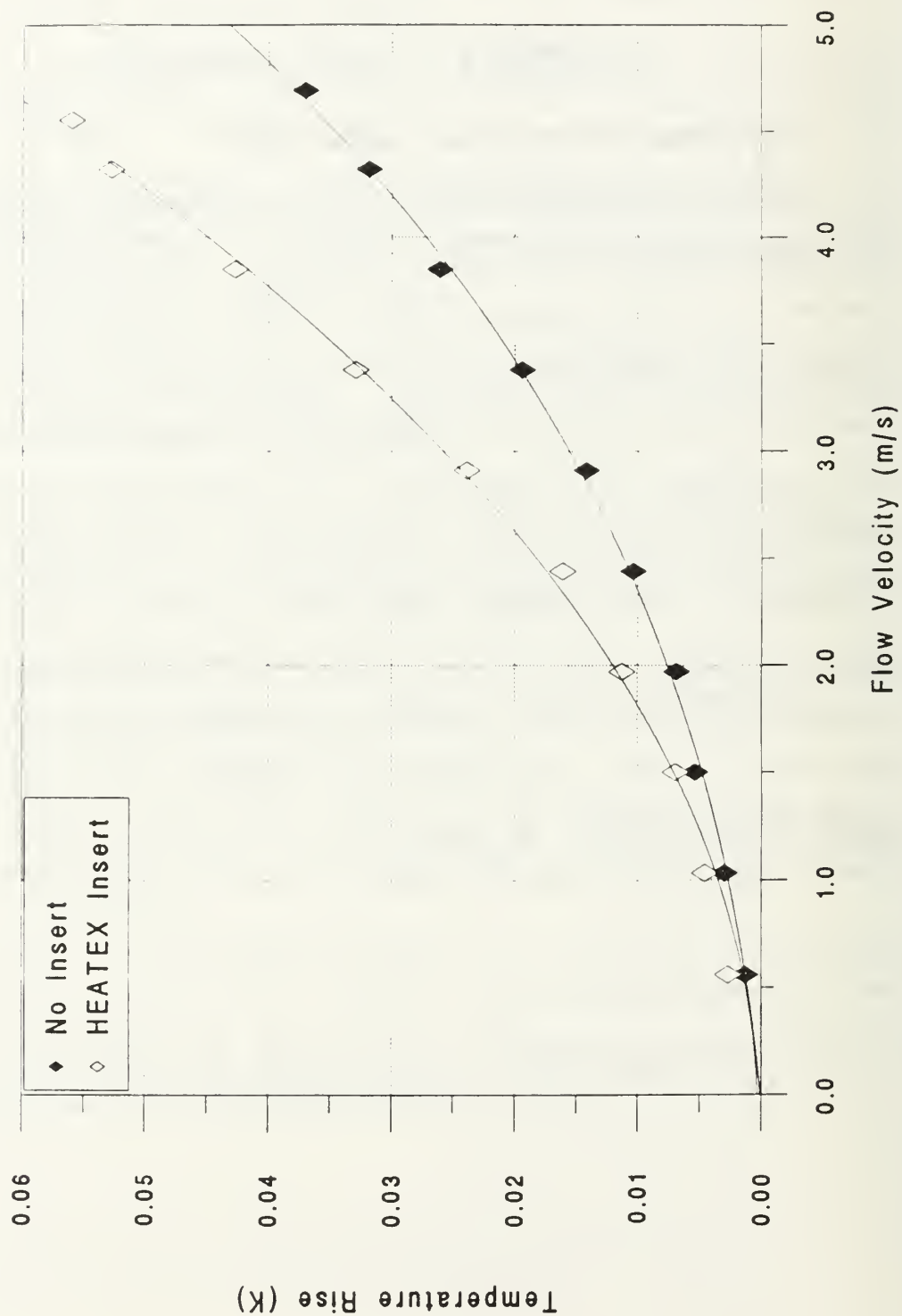


Figure A.1 Frictional Temperature Rise for the MHT Korodense Titanium Tube with and without a HEATEX Insert

Table A. 1 FRICTIONAL TEMPERATURE RISE EQUATIONS FOR MHT KORODENSE TUBE

Inside Condition	Polynomial Equation
HEATEX Insert	$T_{\text{rise}} = \frac{2.564 \times 10^{-4}}{6 (V_w)^3} + \frac{6.263 \times 10^{-4} V_w}{+ 2.603 \times 10^{-3} (V_w)^2} + 7.830 \times 10^{-}$
No Insert	$T_{\text{rise}} = \frac{6.790 \times 10^{-5}}{4 (V_w)^3} + \frac{1.632 \times 10^{-3} V_w}{+ 8.409 \times 10^{-4} (V_w)^2} + 1.111 \times 10^{-}$
where: T_{rise} = Temperature Rise (K) V_w = Fluid Velocity (m/s)	

APPENDIX B. UNCERTAINTY ANALYSIS

All derived quantities have an inherent uncertainty associated with them when their results are obtained from measured values. The uncertainty arises due to inaccuracies in the measurement of the physical quantities used in their calculations. The difference between the actual value and the measured value depends on the accuracy of the measuring device, the calibration of the device, and the experience of the operator. Eventhough the error associated with any single measurement may seem insignificant, it may have a profound effect on the accuracy of the derived quantity due to the calculations made.

Kline and McClintock [Ref. 67] developed a method to estimate the uncertainty in the derived quantity, R , which is a function of several measured variables, $x_1, x_2, \dots, x_n$, as follows:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} W_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} W_n \right)^2 \right]^{1/2} \quad (\text{B.1})$$

where:

W_R is the uncertainty of the desired dependent variable

$x_1, x_2, \dots, x_n$ are the measured independent variables

$W_1, W_2, \dots, W_n$ are the uncertainties in the measured variables

Georgiadis [Ref. 68] presents a complete discussion on the uncertainty analysis used for this experiment. Based on Georgiadis' developments, Mitrou [Ref. 14] wrote a program for calculating the uncertainties in the mathematically derived quantities obtained from data collected using the apparatus utilized in this research. Modifications were made to the program which allow for the data collected on MHT Korodense tubes to be processed. Sample uncertainty results for the following data collection conditions are presented in this appendix.

1. Vacuum pressure with no insert and high flow rate (3.83 m/s).
2. Vacuum pressure with no insert and low flow rate (1.03 m/s).
3. Vacuum pressure with HEATEX insert and high flow rate (3.83 m/s).
4. Vacuum pressure with HEATEX insert and low flow rate (1.02 m/s).
5. Atmospheric pressure with no insert and high flow rate (3.82 m/s).
6. Atmospheric pressure with no insert and low flow rate (1.02 m/s).
7. Atmospheric pressure with HEATEX insert and high flow rate (3.82 m/s).
8. Atmospheric pressure with HEATEX insert and low flow rate (1.02 m/s).

1. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTNV8
 Pressure Condition: Vacuum
 Vapor Temperature = 48.574 (Deg C)
 Water Flow Rate (%) = 80.00
 Water Velocity = 3.83 (m/s)
 Heat Flux = 1.481E+05 (W/m²)
 Tube-metal thermal conduc. = 21.0 (W/m.K)
 Petukov-Popov constant = 2.3857

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.09
Heat Flux, q	1.87
Log-Mean-Tem Diff, LMTD	1.63
Wall Resistance, R _w	4.97
Overall H.T.C., U _o	2.48
Water-Side H.T.C., H _i	7.47
Vapor-Side H.T.C., H _o	6.77

2. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTNV8
 Pressure Condition: Vacuum
 Vapor Temperature = 48.691 (Deg C)
 Water Flow Rate (%) = 20.00
 Water Velocity = 1.03 (m/s)
 Heat Flux = 1.149E+05 (W/m²)
 Tube-metal thermal conduc. = 21.0 (W/m.K)
 Petukov-Popov constant = 2.3857

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	2.99
Reynolds Number, Re	3.08
Heat Flux, q	3.07
Log-Mean-Tem Diff, LMTD	.56
Wall Resistance, R _w	4.97
Overall H.T.C., U _o	3.13
Water-Side H.T.C., H _i	7.81
Vapor-Side H.T.C., H _o	13.98

3. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTHV8
 Pressure Condition: Vacuum
 Vapor Temperature = 48.516 (Deg C)
 Water Flow Rate (%) = 80.00
 Water Velocity = 3.83 (m/s)
 Heat Flux = 1.526E+05 (W/m²)
 Tube-metal thermal conduc. = 21.0 (W/m.K)
 Petukhov-Popov constant = 3.0112

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.09
Heat Flux, q	1.83
Log-Mean-Tem Diff, LMTD	1.58
Wall Resistance, R _w	4.97
Overall H.T.C., U _o	2.42
Water-Side H.T.C., H ₁	5.92
Vapor-Side H.T.C., H _o	6.35

4. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTHV8
 Pressure Condition: Vacuum
 Vapor Temperature = 48.551 (Deg C)
 Water Flow Rate (%) = 20.00
 Water Velocity = 1.02 (m/s)
 Heat Flux = 1.202E+05 (W/m²)
 Tube-metal thermal conduc. = 21.0 (W/m.K)
 Petukhov-Popov constant = 3.0112

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.00
Reynolds Number, Re	3.09
Heat Flux, q	3.08
Log-Mean-Tem Diff, LMTD	.54
Wall Resistance, R _w	4.97
Overall H.T.C., U _o	3.12
Water-Side H.T.C., H ₁	6.36
Vapor-Side H.T.C., H _o	11.54

5. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTNAB
 Pressure Condition: Atmospheric (101 kPa)
 Vapor Temperature = 99.954 (Deg C)
 Water Flow Rate (%) = 80.00
 Water Velocity = 3.92 (m/s)
 Heat Flux = 3.959E+05 (W/m²)
 Tube-metal thermal conduc. = 21.0 (W/m.K)
 Petukov-Popov constant = 2.4659

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.11
Heat Flux, q	1.10
Log-Mean-Tem Diff, LMTD	.61
Wall Resistance, R _w	4.97
Overall H.T.C., U _o	1.26
Water-Side H.T.C., H _i	7.69
Vapor-Side H.T.C., H _o	4.97

6. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTNAB
 Pressure Condition: Atmospheric (101 kPa)
 Vapor Temperature = 99.981 (Deg C)
 Water Flow Rate (%) = 20.00
 Water Velocity = 1.02 (m/s)
 Heat Flux = 3.114E+05 (W/m²)
 Tube-metal thermal conduc. = 21.0 (W/m.K)
 Petukov-Popov constant = 2.4659

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.00
Reynolds Number, Re	3.10
Heat Flux, q	3.04
Log-Mean-Tem Diff, LMTD	.21
Wall Resistance, R _w	4.97
Overall H.T.C., U _o	3.05
Water-Side H.T.C., H _i	8.04
Vapor-Side H.T.C., H _o	13.03

7. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTHA8
 Pressure Condition: Atmospheric (101 kPa)
 Vapor Temperature = 99.924 (Deg C)
 Water Flow Rate (%) = 80.00
 Water Velocity = 3.82 (m/s)
 Heat Flux = 4.083E+05 (W/m²)
 Tube-metal thermal conduc. = 21.0 (W/m.K)
 Petukov-Popov constant = 3.3112

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.11
Heat Flux, q	1.09
Log-Mean-Tem Diff, LMTD	.53
Wall Resistance, R _w	4.97
Overall H.T.C., U _o	1.24
Water-Side H.T.C., H _i	5.68
Vapor-Side H.T.C., H _o	4.25

8. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTHA8
 Pressure Condition: Atmospheric (101 kPa)
 Vapor Temperature = 99.999 (Deg C)
 Water Flow Rate (%) = 20.00
 Water Velocity = 1.02 (m/s)
 Heat Flux = 3.367E+05 (W/m²)
 Tube-metal thermal conduc. = 21.0 (W/m.K)
 Petukov-Popov constant = 3.3112

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.00
Reynolds Number, Re	3.11
Heat Flux, q	3.04
Log-Mean-Tem Diff, LMTD	.19
Wall Resistance, R _w	4.97
Overall H.T.C., U _o	3.05
Water-Side H.T.C., H _i	6.14
Vapor-Side H.T.C., H _o	9.73

APPENDIX C. DRPML PROGRAM LISTING

The data collection and reduction program, DRPML, which was used throughout this study follows:

```

10001 DRPML LONG,
10061 REVISED FROM DRPML: SEP 1992 O'KEEFE,
10071
10081 TO BE USED WITH NON-INSTRUMENTED TUBES ONLY
10091 TAKES DATA IN THE FORMAT OF SWENSEN/O'KEEFE, LONG
10101 CAN REPROCESS ANY NON-INSTRUMENTED DATA
10121
10131 THIS PROGRAM WAS USED TO COLLECT ALL THE NON-
10141 INSTRUMENTED DATA TAKEN BY LONG (JAN-JUN 1993) FOR TITANIUM TUBES
10151
10171 MEANING OF ALL FLAGS IN PROGRAM
10181
10191 IFT: FLUID TYPE
10201 ISO: OPTION WITHIN PROGRAM
10211 IM: INPUT MODE
10221 IWIL: VALUE OF Ci USED
10231 IFG: FINNED OR SMOOTH
10241 INN: INSERT TYPE
10251 IWT: LOOP NO. WITHIN PROGRAM
10261 IWTH: ALTERNATIVE CONDENSER TUBES
10271 IMC: TUBE MATERIAL
10281 ITDS: TUBE DIAMETER
10291 IPC: PRESSURE CONDITION
10301 INF: DIMENSIONLESS FILE REQUIRED
10311 IPF: PLOT FILE REQUIRED
10321 IOV: OUTPUT REQUIRED
10331 IHI: INSIDE HTC CORRELATION
10341 IOC: OUTSIDE HTC THEORY/CORRELATION
1035 COM /Cc/ C(7)
1036 COM /Cc55/ T55(5)
1037 COM /Cc56/ T56(5)
1038 COM /Cc57/ T57(5)
1039 COM /Cc58/ T58(5)
1040 COM /FId/ Ift,Istu
1041 DIM Emf(20),Tw(6)
1042 COM /Pr/ Qpa(42),Tfm(42),Tfmr,Ipc,Qpr
1043 COM /Wil/ Nrun,Itm,Iwth,Imc,Ife,Ijob,Iwd,Ifg,IpcO,IftO,IwIl,IhI,Ioc,Inam,K
cu,Re,p,Rm,Ax
1044 COM /Geom/ D1,D2,D1,Do,L,L1,L2
1045 COM /Fric/ Istuo,Inn,Iwtho,Uw,Uws,Inamo
1047 DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1048 DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1049 READ C(*)
1050 DATA 273.15,2.5943E-2,-7.2671E-7,3.2941E-11,-9.7719E-16,9.7121E-20
1051 READ T55(*)
1052 DATA 273.15,2.5878E-2,-5.9853E-7,-3.1242E-11,1.3275E-14,-1.0188E-18

```

```

1053 READ T56(*)
1054 DATA 273.15,2.5923E-2,-7.3933E-7,2.8625E-11,1.9717E-15,-2.2486E-19
1055 READ T57(*)
1056 DATA 273.15,2.5931E-2,-7.5232E-7,4.0657E-11,-1.2791E-15,6.4402E-20
1057 READ T58(*)
1058 Or=.015875      ! Outside diameter of the outlet end
1059 Dssp=.1524      ! Inside diameter of stainless steel test section
1060 Ax=PI*Dssp 2/4
1061 Alp2=0.
1062 L=.13335        ! Condensing length
1063 L1=.060325      ! Inlet end "fin length"
1064 L2=.034925      ! Outlet end "fin length"
1065 PRINTER IS 1
1066 BEEP
1067 PRINT USING "4X,""Select option:"""
1069 PRINT USING "6X,"" 0 Take data or re-process previous data""
1090 PRINT USING "6X,"" 2 WILSON Analysys""
1106 INPUT Iso
1108 Iso=Iso+1
1111 IF Iso 1 THEN 3094
1112 BEEP
1115 INPUT "SELECT FLUID (0=WATER, 1=R-113, 2=EG)",Ift
1116 Ifto=Ift
1117 BEEP
1118 Ijob=0
1119 INPUT "ENTER INPUT MODE (0=3054A,1=FILE)",Im
1120 Im=Im+1
1123 BEEP
1124 IF Im=1 THEN
1126     INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1129     OUTPUT 709;"TD";Date$
1132     OUTPUT 709;"TD"
1133     ENTER 709;Date$
1135 END IF
1136 IF Ijob=1 THEN
1138     BEEP
1141     INPUT "SKIP PAGE AND HIT ENTER",Ok
1144 END IF
1145 PRINTER IS 701
1146 IF Im=1 THEN
1148     ENTER 709;Date$
1150     PRINT "          Month, date and time :";Date$
1151 END IF
1153 PRINT
1156 PRINT USING "10X,""NOTE: Program name : DRPML""
1171 IF Ijob=1 THEN 1189

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```

1174 BEEP
1186 INPUT "SELECT (C1:0=FIND,1=STORED C1)",Iw1
1189 IF Im=1 THEN
1192 BEEP
1195 INPUT "GIVE A NAME FOR THE RAW DATA FILE",D_file$
1198 PRINT USING "16x","File name      : ",14A";D_file$
1201 CREATE BDAT D_file$,30
1204 ASSIGN @File TO D_file$
1207 BEEP
1210 INPUT "ENTER GEOMETRY CODE (1=FINNED,0=PLAIN)",Ifg
1211 Inn=0
1212 PRINTER IS 1
1216 BEEP
1217 PRINT "    ENTER INSERT TYPE:"
1218 PRINT "        0=NONE (DEFAULT)"
1219 PRINT "        1=TWISTED TAPE"
1220 PRINT "        2=WIRE WRAP"
1221 PRINT "        3=HEATEX"
1222 INPUT Inn
1225 OUTPUT @File;Ifg,Inn
1227 Iwt=0  ! FOR UNINSTRUMENTED TUBE
1228 Fh=0
1231 Fp=0
1234 Fw=0
1235 Istu=0
1236 Istuo=Istu
1238 IF Ifg=0 THEN 1241
1239 INPUT "FIN PITCH, HEIGHT AND WIDTH IN MM, Fp,Fh,Fw",Fp,Fh,Fw
1241 OUTPUT @File;Iwt,Fp,Fw,Fh
1242 ELSE
1249 BEEP
1250 PRINTER IS 1
1252 PRINT "  STUDENT'S DATA TO BE REPROCESSED:"
1253 PRINT "    0=SWENSEN/O'KEEFE/LONG (DEFAULT)"
1254 PRINT "    1=VAN PETTEN/MITROU/COUMES/GUTTENDORF"
1255 INPUT Istu
1256 Istuo=Istu
1258 BEEP
1259 PRINT
1260 IF Istu=1 THEN
1261 PRINT "  STUDENT NAME:"
1262 PRINT "    0=VAN PETTEN"
1263 PRINT "    1=MITROU"
1264 PRINT "    2=COUMES"
1265 PRINT "    3=GUTTENDORF"
1266 ELSE

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```

1267      PRINT " 4=SWENSEN"
1268      PRINT " 5=O'KEEFE"
1269      PRINT " 6=LONG"
1271  END IF
1272  INPUT Inam
1273  Inamo=Inam
1275  BEEP
1276  INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D_file$
1277  PRINTER IS 701
1278  IF Inam=0 THEN PRINT USING "16X, ""Data taken by          : VAN PETT
EN"" ""
1279  IF Inam=1 THEN PRINT USING "16X, ""Data taken by          : MITROU""
"
1280  IF Inam=2 THEN PRINT USING "16X, ""Data taken by          : COUMES""
"
1281  IF Inam=3 THEN PRINT USING "16X, ""Data taken by          : GUTTENDO
RF"" ""
1282  IF Inam=4 THEN PRINT USING "16X, ""Data taken by          : SWENSEN"
""
1283  IF Inam=5 THEN PRINT USING "16X, ""Data taken by          : O'KEEFE"
""
1284  IF Inam=6 THEN PRINT USING "16X, ""Data taken by          : LONG"" ""
1285  PRINT USING "16X, ""This analysis done on file : "",10A";D_file$
1286  PRINTER IS 1
1287  BEEP
1288  INPUT "ENTER NUMBER OF DATA SETS STORED",Nrun
1289  ASSIGN @File TO D_file$
1290  ENTER @File;Ifg,Inn
1291  IF Istu=0 THEN
1292      ENTER @File;Iwt,Fp,Fw,Fh
1293  ELSE
1294      IF Ifg=0 THEN ENTER @File;Iwt
1295      IF Ifg=1 THEN ENTER @File;Fp,Fw,Fh
1296  END IF
1297  END IF
1298  IF Ijob=1 THEN 1537
1299  IF Ift=0 THEN 1345
1300  BEEP
1301  PRINTER IS 1
1302  PRINT USING "4X, ""Select tube type: ""
1303  PRINT USING "6X, ""0 Copper Tube""
1306  PRINT USING "6X, ""1 Wolverine Korodense LPD Titanium Tube""
1320  PRINT USING "6X, ""2 Smooth Titanium Tube""
1321  PRINT USING "6X, ""3 Wolverine Korodense MHT Titanium Tube""
1323  INPUT Iwth
1324  Iwtho=Iwth

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1326 BEEP
1327 PRINT USING "4X","Select tube Enhancement used:"""
1328 PRINT USING "6X","0 SMOOTH TUBE""
1329 PRINT USING "6X","1 FINNED TUBE""
1330 PRINT USING "6X","2 WIRE-WRAPPED SMOOTH TUBE""
1331 PRINT USING "6X","3 LPD KORODENSE TUBE""
1332 PRINT USING "6X","4 WIRE-WRAPPED LPD KORODENSE TUBE""
1333 PRINT USING "6X","5 MHT KORODENSE TUBE""
1334 PRINT USING "6X","6 WIRE-WRAPPED MHT KORODENSE TUBE""
1335 INPUT Ityp
1336 PRINTER IS 701
1337 BEEP
1338 PRINTER IS 1
1339 PRINT USING "4X","Select Material Code:"""
1340 PRINT USING "6X","0 Copper      1 Stainless steel""
1341 PRINT USING "6X","2 Aluminum  3 90:10 Cu-Ni""
1342 PRINT USING "6X","4 Titanium  ""
1343 INPUT Imc
1344 PRINTER IS 1
1345 BEEP
1346 Itds=1
1351 IF Iwth=0 THEN
1352     PRINT USING "4X","SELECT TUBE DIA TYPE:"""
1357     PRINT USING "6X","0  SMALL""
1360     PRINT USING "6X","1  MEDIUM (DEFAULT)""
1363     PRINT USING "6X","2  LARGE""
1366     INPUT Itds
1367 END IF
1369 PRINTER IS 701
1372 IF Iwth=0 THEN
1375     D1=.0127      ! ID OF MEDIUM & LARGE TUBES
1378     Do=.01905    ! OD OF MEDIUM TUBE
1383 END IF
1384 IF Iwth=1 THEN
1399     D1=.01347
1402     Do=.01585
1405 END IF
1457 IF Iwth=2 THEN
1458     Do=.01585
1459     D1=.01386
1460 END IF
1461 IF Iwth=3 THEN
1462     Do=.01607
1463     D1=.01353
1464 END IF
1466 D1=.01905

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```

1467 D2=.01587
1468 IF Itds=0 THEN
1469     Do=.0127
1471     Di=.009525
1474 END IF
1477 IF Itds=2 THEN Do=.025
1478 IF Iwth=1 OR Iwth=3 THEN D1=.01585
1479 IF Iwth=1 OR Iwth=3 THEN D2=.01585
1484 IF Iwth=2 THEN D1=.01587
1485 IF Iwth=2 THEN D2=.01587
1487 IF Imc=0 THEN Kcu=385
1489 IF Imc=1 THEN Kcu=16
1492 IF Imc=2 THEN Kcu=167
1495 IF Imc=3 THEN Kcu=45
1497 IF Imc=4 THEN Kcu=21.0
1498 Rm=Do*LOG(Do/Di)/(2*Kcu) Wall resistance based on outside area
1501 BEEP
1504 INPUT "ENTER PRESSURE CONDITION (0=V,1=A)",Ipc
1507 Ipc0=Ipc
1508 Inf=0
1510 BEEP
1537 Ife=1
1538 PRINTER IS 701
1543 PRINT USING "16X","This analysis includes end-fin effect""
1546 PRINT USING "16X","Thermal conductivity      = ",30.0,"" (W/m.K)"";Kcu
1549 PRINT USING "16X","Inside diameter, Di      = ",00.00,"" (mm)"";Di*1000
1552 PRINT USING "16X","Outside diameter, Do     = ",00.00,"" (mm)"";Do*1000
1556 Ihi=0
1557 PRINTER IS 1
1558 PRINT "      SELECT INSIDE CORRELATION:"
1559 PRINT "          0=SIDER-TATE (DEFAULT)"
1560 PRINT "          1=SLEICHER-ROUSE"
1561 PRINT "          2=PETUKHOV-POPOV"
1562 INPUT Ihi
1563 IF Ihi=0 THEN
1564     BEEP
1566     INPUT "      SELECT REYNOLDS EXPONENT",Rexp
1567 END IF
1568 Ioc=0
1569 BEEP
1570 PRINT
1571 PRINT "      SELECT OUTSIDE THEORY/CORRELATION FOR WILSON ANALYSIS:"
1572 PRINT "          0=NUSSELT THEORY (DEFAULT)"
1573 PRINT "          1=FUJII (1979) CORRELATION"
1574 INPUT Ioc
1575 BEEP

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1576 Itm=1
1577 PRINT
1578 PRINT "      SELECT COOLANT TEMPERATURE RISE MEASUREMENT:"
1579 IF Istu=0 THEN PRINT "      0=SINGLE TEFLON T/C"
1580 PRINT "      1=QUARTZ THERMOMETER (DEFAULT)"
1581 PRINT "      2=10-JUNCTION THERMOPILE"
1582 INPUT Itm
1583 PRINTER IS 701
1584 IF Itm=0 THEN PRINT USING "16X,""This analysis uses the SINGLE TEFLON T/C
readings""
1585 IF Itm=1 THEN PRINT USING "16X,""This analysis uses the QUARTZ THERMOMETER
readings""
1586 IF Itm=2 THEN PRINT USING "16X,""This analysis uses the 10-JUNCTION THERMO
PILE readings""
1587 Iic=1 ) FOR MODIFIED WILSON
1588 IF Ihi=0 THEN Ci=.027
1589 IF Ihi=1 THEN Ci=1.
1590 IF Ihi=2 THEN Ci=1.
1591 IF Iwi=1 THEN
1601     BEEP
1602     INPUT "ENTER C1 IF DIFFERENT FROM STORED VALUE",C1
1603 END IF
1604 PRINTER IS 701
1605 IF Ihi=0 THEN PRINT USING "16X,""Modified Sieder-Tate coefficient    = "" ,Z
.40";Ci
1606 IF Ihi=0 THEN PRINT USING "16X,""Chosen Reynolds No. exponent      = "" ,D
.DD";Reap
1607 IF Ihi=1 THEN PRINT USING "16X,""Modified Sletcher-Rouse coefficient  = "
",Z.40";Ci
1608 IF Ihi=2 THEN PRINT USING "16X,""Modified Petukhov-Popov coefficient  = "
",Z.40";Ci
1609 IF Inn=0 THEN PRINT USING "16X,""Using no insert inside tube""
1610 IF Inn=2 THEN PRINT USING "16X,""Using wire wrap insert inside tube""
1611 IF Inn=3 THEN PRINT USING "16X,""Using HEATEX insert inside tube""
1612 IF Istu=0 THEN
1613     IF Inn=1 THEN PRINT USING "16X,""Using twisted tape insert inside tube"
""
1614 ELSE
1615     IF Inn=1 THEN PRINT USING "16X,""Using wire wrap insert inside tube""
1616 END IF
1619 IF Iic=0 AND Ife=1 THEN Ac=26.4
1620 IF Iic=1 THEN Ac=0.
1621 BEEP
1622 IF Ijob=1 THEN 1648
1623 PRINTER IS 1
1624 INPUT "NAME FOR A TEMPORARY PLOT FILE (TO BE PURGED)",P_file$

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1625 P_file$="DUMMY"
1626 BEEP
1634 CREATE BDATA P_file$,10
1644 ASSIGN @Filep TO P_file$
1648 IF Ijob=1 THEN
1651     Iov=1
1654     GOTO 1657
1657 END IF
1660 BEEP
1661 INPUT "SELECT OUTPUT (0=SHORT, 1=LONG)",Iov
1666 Iov=Iov+1
1667 PRINTER IS 701
1672 IF Ityp=0 THEN PRINT USING "16X,""Tube Enhancement : SMOOTH TUBE""
1673 IF Ityp=1 THEN PRINT USING "16X,""Tube Enhancement : FINNED TUBE""
1674 IF Ityp=2 THEN PRINT USING "16X,""Tube Enhancement : WIRE-WRAPPED SMOOTH
TUBE""
1675 IF Ityp=3 THEN PRINT USING "16X,""Tube Enhancement : LPD KORODENSE TUBE"
""
1678 IF Ityp=4 THEN PRINT USING "16X,""Tube Enhancement : WIRE-WRAPPED LPD KO
RODENSE TUBE""
1679 IF Ityp=5 THEN PRINT USING "16X,""Tube Enhancement : MHT KORODENSE TUBE"
""
1680 IF Ityp=6 THEN PRINT USING "16X,""Tube Enhancement : WIRE-WRAPPED MHT KO
RODENSE TUBE""
1682 BEEP
1683 IF Imc=0 THEN PRINT USING "16X,""Tube material : COPPER""
1684 IF Imc=1 THEN PRINT USING "16X,""Tube material : STAINLESS-STEEL""
1685 IF Imc=2 THEN PRINT USING "16X,""Tube material : ALUMINUM""
1686 IF Imc=3 THEN PRINT USING "16X,""Tube material : 90/10 CU/NI""
1687 IF Imc=4 THEN PRINT USING "16X,""Tube material : TITANIUM""
1688 IF Ipc=0 THEN PRINT USING "16X,""Pressure condition : VACUUM""
1689 IF Ipc=1 THEN PRINT USING "16X,""Pressure condition : ATMOSPHERIC""
1690 PRINT USING "16X,""Fin pitch, width, and height (mm): ",DD.DD,2X,Z.DD,2X,
Z.DD";Fp,Fw,Fh
1691 IF (Iw1=0 OR Iw1=2) AND Im=2 THEN
1692     Ijob=1
1693     Iwd=1
1696     CALL Wilson(C1)
1699 END IF
1702 J=0
1712 IF Iov=1 THEN
1722 PRINT
1723 IF Ihi=1 THEN
1724     PRINT USING "10X,""Data Vw Uo Ho Qp Tcf
Ts Rexp""
1725     PRINT USING "10X,"" # (m/s) (W/m^2-K) (W/m^2-K) (W/m^2) (C)

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1700 S-R)""
1705 ELSE
1708 PRINT USING "10X," "Data" Vw Up Ho Qp
1710 Tof Ts""
1728 PRINT USING "10X," " # " m/s " W/m 2-H " W/m 2-H " W/m 2-
1730 END IF
1740 END IF
1747 Zx=0
1750 Zx2=0
1753 Zxy=0
1756 Zy=0
1759 Sx=0
1762 Sy=0
1765 Sxs=0
1768 Sxy=0
1771 Go_on=1
1774 Repeat:1
1777 J=J+1
1780 IF Im=1 THEN
1783 BEEP
1786 INPUT "LIKE TO CHECK NG CONCENTRATION (1=Y,0=N)?",Ng
1789 IF J=1 THEN
1792 OUTPUT 709;"AR AF40 AL41 VRS"
1795 OUTPUT 709;"AS SA"
1798 END IF
1801 BEEP
1804 INPUT "ENTER FLOWMETER READING",Fm
1807 OUTPUT 709;"AR AF60 AL62 VRS"
1810 OUTPUT 709;"AS SA"
1813 ENTER 709;Etp
1816 OUTPUT 709;"AS SA"
1819 BEEP
1822 INPUT "CONNECT VOLTAGE LINE",Ok
1825 ENTER 709;Bvol
1828 BEEP
1831 INPUT "DISCONNECT VOLTAGE LINE",Ok
1834 IF Bvol<.1 THEN
1837 BEEP
1840 BEEP
1843 INPUT "INVALID VOLTAGE, TRY AGAIN!",Ok
1846 GOTO 1819
1849 END IF
1858 OUTPUT 709;"AS SA"
1861 ENTER 709;Bamp
1862 Etp=Etp*1.E+6

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1863 OUTPUT 709;"AR AF40 AL47 VRS"
1874 Nn=7
1875 FOR I=0 TO Nn
1878 OUTPUT 709;"AS SA"
1885 Se=0
1888 FOR K=1 TO 10
1891 ENTER 709;E
1894 Se=Se+E
1897 NEXT K
1900 Emf(I)=ABS(Se/10)
1916 Emf(I)=Emf(I)*1.E+6
1918 NEXT I
1921 OUTPUT 709;"AS SA"
1924 OUTPUT 713;"T1R2E"
1927 WAIT 2
1930 ENTER 713;T11
1933 OUTPUT 713;"T2R2E"
1936 WAIT 2
1939 ENTER 713;T2
1942 OUTPUT 713;"T1R2E"
1945 WAIT 2
1948 ENTER 713;T12
1951 T1=(T11+T12)*.5
1954 OUTPUT 713;"T3R2E"
1960 BEEP
1970 INPUT "ENTER PRESSURE GAGE READING (Pga)",Pga
1971 Pvp1=Pga*6894.7 / PSI TO Pa
1972 OUTPUT 709;"AR AF64 AL64 VRS"
1973 OUTPUT 709;"AS SA" / PRESSURE TRANSDUCER
1974 Ss=0
1975 FOR K=1 TO 20
1976 ENTER 709;Etran
1977 Ss=Ss+Etran
1978 NEXT K
1979 Ptran=ABS(Ss/20)
1980 BEEP
1981 PRESSURE IN Pa FROM TRANSDUCER
1982 Pvp2=(-2.93604*Ptran+14.7827)*6894.7
1985 ELSE
1986 IF Istu=0 THEN
1989 ENTER @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvp1,Pvp2,Emf(*)
1990 ELSE
1992 ENTER @File;Bvol,Bamp,Utran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),F
m,T1,T2,Phg,Pwater
1994 END IF
1996 IF J=1 OR J=20 OR J=Nrun THEN

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```

1997         Ng=1
1998     ELSE
1999         Ng=0
2000     END IF
2002 END IF
2003 IF Istu=0 THEN
2008     Tsteam1=FNTvsv57(Emf(0))
2009     Tsteam1=Tsteam1-273.15
2010     Tsteam2=FNTvsv56(Emf(1))
2011     Tsteam2=Tsteam2-273.15
2012     Tsteam=Tsteam1
2015     Troom=FNTvsv58(Emf(2))
2023     Troom=Troom-273.15
2038     Tcon=FNTvsv58(Emf(7))
2039     Tcon=Tcon-273.15
2042 ELSE
2043     Tsteam=FNTvsv(Emf(0))
2044     Troom=FNTvsv(Emf(3))
2045     Tcon=FNTvsv(Emf(4))
2046 END IF
2048 Psat=FNpvst(Tsteam)
2050 Rohg=13529-122*(Troom-26.85)/50
2053 Rowater=FNrhov(Troom)
2063 IF Istu=0 THEN
2081     Ptest1=Pvap1
2082     Ptest2=Pvap2
2083 ELSE
2084     Ptest2=(Phg*Rohg-Pwater*Rowater)*9.81/1000
2085 END IF
2087 Pks=Psat*1.E-3
2088 Plp=Ptest2*1.E-3
2089 Pkt=Pks
2092 Tsat=FNTvsp(Psat)
2098 Ust=FNvst(Tsteam)
2104 Ppng=(Ptest2-Psat)/Ptest2
2121 Ppst=1-Ppng
2122 Muv=18.016
2123 IF Ift=1 THEN Muv=137    ! TO BE CORRECTED
2124 IF Ift=2 THEN Muv=62
2125 Vfng=(Ptest2-Psat)/Ptest2
2126 Mfng=1/(1+(1/Vfng-1)*Muv/28.97)
2127 Mfng=Mfng*100
2128 Vfng=Vfng*100
2131 BEEP
2134 IF Iov=2 THEN
2137     PRINT

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21381 RECORD TIME OF TAKING DATA
2139 IF Im=1 THEN
2140 OUTPUT 709;"TD"
2141 ENTER 709;Told$
2142 END IF
2144 PRINT USING "10X, ""Data set number "" = "" ,00,4X,14A"";J,Told$
2145 OUTPUT 709;"AR AF40 AL40 VRS"
2146 OUTPUT 709;"AS SA"
2149 END IF
2152 IF Iov=2 AND Ng=1 THEN
2155 PRINT USING "10X, "" Psat Ptran Tmeas Tsat NG %""
2158 PRINT USING "10X, "" (kPa) (kPa) (C) (C) Molal ""
2161 PRINT USING "11X,1(30.00,2X),1(30.00,3X),2(30.00,2X),2X,1(M30.0,2X)":Pks,
Pkp,Tsteam,Tsat,Mfng
2164 PRINT
2167 END IF
2170 IF Mfng .5 THEN
2173 BEEP
2176 IF Im=1 AND Ng=1 THEN
2179 BEEP
2182 PRINT
2185 PRINT USING "10X, ""Energize the vacuum system ""
2188 BEEP
2191 INPUT "OK TO ACCEPT THIS RUN (1=Y,0=N)?",Ok
2194 IF Ok=0 THEN
2197 BEEP
2200 DISP "NOTE: THIS DATA SET WILL BE DISCARDED!! "
2203 WAIT 5
2206 GOTO 1780
2209 END IF
2212 END IF
2215 END IF
2218 IF Im=1 THEN
2221 IF Fm<10 OR Fm 100 THEN
2224 Ifm=0
2227 BEEP
2230 INPUT "INCORRECT FM (1=ACCEPT,0=DELETE)",Ifm
2233 IF Ifm=0 THEN 1804
2236 END IF
2239 END IF
2242 ANALYSIS BEGINS
2243 IF Istu=0 THEN
2252 T11=FNTvsv58(Emf(3))
2262 T12=FNTvsv55(Emf(5))
2272 T01=FNTvsv58(Emf(4))
2282 T02=FNTvsv55(Emf(6))

```

```

2292      T11=T11-273.15
2302      T12=T12-273.15
2312      T01=T01-273.15
2322      T02=T02-273.15
2332      Tdel1=T01-T11
2342      Tdel2=T02-T12
2352      Tdel3=T2-T1
2353      Etp1=Emf(3)+Etp/20.
2354      Dtde=2.5931E-2-1.50464E-6*Etp1+1.21701E-10*Etp1^2-5.1164E-15*Etp1^3+3.2
201E-19*Etp1^4
2355      Tris=Dtde*Etp/10.
2358      To3=T11+Tris
2359      IF Iov=2 THEN
2361          PRINT USING "1X," TINI TOUT1 TIN3 TOUT3 DELT1 DELT3 T
PILE ""
2362          PRINT USING "1X," (TEFLON) (QUARTZ) ""
2364          PRINT USING "2X,7:3D.00,2X":T11,T01,T1,T2,Tdel1,Tdel3,Tris
2365      END IF
2367      Er1=ABS(T11-T1)
2368      Er3=ABS(T12-T1)
2369      PRINTER IS 1
2370      BEEP
2375      Er2=ABS((T2-T1)-(Tris))/(T2-T1)
2377      IF Er2 .05 AND Im=1 THEN
2378          BEEP
2379          PRINT "QCT AND T-PILE DIFFER BY MORE THAN 5%"
2380          Ok2=1
2381          IF Ok2=0 AND Er2 .05 AND Im=1 THEN 1780
2382      END IF
2383      PRINTER IS 701
2394  ELSE
2385      T1=FNT/sv(Emf(2))
2386      Grad=FNGrad/(T1+T2)*.5)
2387      To=T1+ABS(Etp)/(10*Grad)*1.E+6
2388      T11=T1
2389      To3=To
2391  END IF
2392  IF Istu=0 AND Itm=0 THEN
2393      T11=T11
2394      T2o=T01
2395  END IF
2396  IF Itm=1 THEN
2397      T11=T1
2398      T2o=T2
2399  END IF
2400  IF Itm=2 THEN

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```

2401      T11=T11
2402      T2o=T2o3
2403  END IF
2404  Tavg=(T11+T2o)/.5
2405  Ift=0
2406  Cpw=FNCPw(Tavg)
2407  Rhow=FNRRhow(Tavg)
2408  IF Istu=0 THEN
2409      Md=(6.7409*Fm+13.027)/1000.
2410      Md=Md*(1.0365-1.96644E-3*T11+5.252E-6*T11^2)/1.0037
2411  ELSE
2412      Md=1.04805E-2+6.80932E-3*Fm
2413      Md=Md*(1.0365-1.96644E-3*T11+5.252E-6*T11^2)/.995434
2414  END IF
2415  Mf=Md/Rhow
2416  Uw=Mf/(PI*D1^2/4)
2417  Uws=Uw*(D1/1.27E-2)^2
2418  Tcor=FNTRcor(T2o)
2419  T2o=Tcor
2420  Q=Md*Cpw*(T2o-T11)
2421  Qp=Q/(PI*Do*L)
2422  Ift=0
2423  Kw=FNKW(Tavg)
2424  Muw=FNMuw(Tavg)
2425  Re1=Rhow*Uw*D1/Muw ! ASSUMED SAME FOR KORODENSE
2426  Prw=FNPRw(Tavg)
2427  Fe1=0.
2428  Fe2=0.
2429  Cf=1.
2430  Prwf=Prw
2431  Reif=Re1
2432  IF Ih1=0 THEN
2433      Ome=Re1^Reip*Prw^1.3333*Cf
2434  END IF
2435  IF Ih1=1 THEN
2436      Sra=.88-(.24/(4.+Prwf))
2437      Srb=.333333+.5*EXP(-.6*Prwf)
2438      Ome=(5+.015*Reif^Sra*Prwf^Srb)
2439  END IF
2440  IF Ih1=2 THEN
2441      Eps1=(1.82*LGT(Re1)-1.64)^(-2)
2442      Ppk1=1.+3.4*Eps1
2443      Ppk2=11.7+1.8*Prw^(-1/3)
2444      Pp1=(Eps1/8)*Re1*Prw
2445      Pp2=(Ppk1+Ppk2*(Eps1/8)^.5*(Prw^-.6666-1))
2446      Ome=Pp1/Pp2

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```

2479 END IF
2481  $H_1 = Prw / (D_1 \cdot C_1 \cdot \Delta T_{me})$ 
2482 IF Ife=0 THEN GOTO 2491
2483  $P_1 = P_1 \cdot (D_0 + D_1)$ 
2484  $A_1 = (D_1 - D_1) \cdot P_1 \cdot (D_1 + D_1) \cdot .5$ 
2485  $M_1 = (H_1 \cdot P_1 / (K_{ou} \cdot A_1)) \cdot .5$ 
2486  $P_2 = P_1 \cdot (D_1 + D_2)$ 
2487  $A_2 = (D_2 - D_1) \cdot P_1 \cdot (D_1 + D_2) \cdot .5$ 
2488  $M_2 = (H_1 \cdot P_2 / (K_{ou} \cdot A_2)) \cdot .5$ 
2489  $Fe_1 = FNTanh(M_1 \cdot L_1) / (M_1 \cdot L_1)$ 
2490  $Fe_2 = FNTanh(M_2 \cdot L_2) / (M_2 \cdot L_2)$ 
2491  $Dt = Q / (PI \cdot D_1 \cdot (L + L_1 \cdot Fe_1 + L_2 \cdot Fe_2) \cdot H_1)$ 
2492 IF Ihi=0 THEN
2494  $Cfc = (Muw / FNMuw(Tavg + Dt)) \cdot .14$ 
2495 IF ABS((Cfc - Cf) / Cfc) > .001 THEN
2497  $Cf = (Cf + Cfc) \cdot .5$ 
2500 GOTO 2461
2501 END IF
2503 END IF
2504 IF Ihi=1 THEN
2505  $Prwfc = FNPPrw(Tavg + Dt)$ 
2506  $Reifc = Uv \cdot D_1 \cdot FNRhow(Tavg + Dt) / FNMuw(Tavg + Dt)$ 
2507 IF ABS((Prwfc - Prwf) / Prwfc) > .001 OR ABS((Reifc - Reif) / Reifc) > .001 THEN
2508  $Prwf = (Prwfc + Prwf) / 2.$ 
2509  $Reif = (Reifc + Reif) / 2.$ 
2510 GOTO 2461
2511 END IF
2513 END IF
2516 Ift=Ifto
2517  $Lmtd = (T_{2o} - T_{1i}) / \log((T_{steam} - T_{1i}) / (T_{steam} - T_{2o}))$ 
2518  $U_o = Q / (Lmtd \cdot PI \cdot D_o \cdot L)$ 
2519  $Ho = 1 / (1 / U_o - D_o \cdot L / (D_1 \cdot (L + L_1 \cdot Fe_1 + L_2 \cdot Fe_2) \cdot H_1) - R_m)$ 
2520  $T_{cf} = Q_p / Ho$ 
2521  $Cp_{sc} = FNCpw((T_{con} + T_{steam}) \cdot .5)$ 
2522  $Hfg = FNHfg(T_{steam})$ 
2524  $T_{wo} = T_{steam} - Q_p / Ho$ 
2527  $T_{film} = T_{steam} / 3 + T_{wo} \cdot 2 / 3$ 
2530  $K_f = FNKw(T_{film})$ 
2533  $Rhof = FNRhow(T_{film})$ 
2536  $Muf = FNMuw(T_{film})$ 
2539  $Hpq = .651 \cdot K_f \cdot (Rhof^2 \cdot 9.81 \cdot Hfg / (Muf \cdot D_o \cdot Q_p))^{\cdot .3333}$ 
2541  $Hnuss = .728 \cdot (K_f^3 \cdot 9.81 \cdot Hfg \cdot Rhof^2 / (Muf \cdot D_o \cdot T_{cf}))^{\cdot .25}$ 
2542  $Alp_1 = .728 \cdot Ho / Hnuss$ 
2548  $T_{fm}(J-1) = T_{film}$ 
2551  $Q_{pa}(J-1) = Q_p$ 
2554  $Y = Hoq \cdot Q_p^{\cdot .3333}$ 

```

```

2557   X=Qp
2560   Sx=Sx+X
2563   Sy=Sy+Y
2566   Sxs=Sxs+X2
2569   Sxy=Sxy+X*Y
2572   Q1=500
2575   Qloss=Q1/(100-25)*(Tsteam-Troom)  ! TO BE MODIFIED
2578   Hfc=FNHf(Tcon)
2584   Mdv=0
2587   Bp=(Bvol*100)1/2/5.76
2590   Hsc=Qpsc*(Tsteam-Tcon)
2593   Mdv=((Bp-Qloss)-Mdv*Hsc)/Hfg
2596   IF ABS((Mdv-Mdv)/Mdv) .01 THEN
2599       Mdv=(Mdv+Mdv)*.5
2602       GOTO 2593
2605   END IF
2608   Mdv=(Mdv+Mdv)*.5
2611   Ug=FNUGst(Tsteam)
2614   Uv=Mdv*Ug/Ax
2620   F=(9.81*Do*Muf*Hfg)/(Uv2*Kf*(Tsteam-Two))
2623   Nu=Ho*Do/Kf
2626   Ret=Uv*Rhof*Do/Muf
2629   Nr=Nu/Ret.5
2630   Hfuj=.96*(9.81*Hfg/Tcf).2*Kf.8*Uv.1*Rhof.5/(Do*Muf).3
2635   IF Iov=2 THEN
2645       PRINT
2647       PRINT USING "5X,"" Uv      Re1      H1      Uo      Hfuj(DT)
          Hnu(Q)""
2650       PRINT USING "5X,Z.00,1X,3(MZ.30E,1X),3X,2(MZ.30E,3X)";Uv,Re1,H1,Uo,Hfuj
          ,Hnu
2651       PRINT
2653       PRINT USING "5X,"" Uv      Ho      q      Tcf      NuRe      F
          Hnu(DT)""
2655       PRINT USING "5X,Z.00,1X,2(MZ.30E,1X),2X,3D.00,2X,3(MZ.30E,1X)";Uv,Ho,Qp
          ,Tcf,Nr,F,Hnu
2656       PRINT
2658   END IF
2659   IF Iov=1 THEN
2660       IF Ih1=1 THEN
2661           PRINT USING "11X,00,2X,Z.00,1X,3(MD.30E,1X),2(3D.00,1X),0.000";J,Uv,Uo,
          Ho,Qp,Tcf,Tsteam,Sra
2662       ELSE
2668           PRINT USING "11X,00,4X,Z.00,2X,2(MD.30E,2X),Z.30E,3X,3D.00,2X,3D.00";J,Uv
          ,Uo,Ho,Qp,Tcf,Tsteam
2671       END IF
2674   END IF

```

```

2675 IF Im=1 THEN
2684 IF Iw1=0 AND Ijob=1 OR Iw1=1 THEN OUTPUT @Filep;Qp,Ho
2694 END IF
2707 BEEP
2708 IF Im=1 THEN
2709 IF Iw1=0 AND Ijob=1 OR Iw1=1 THEN OUTPUT @Filep;Qp,Ho
2711 INPUT "CHANGE TO COOL RISE? 1=Y, 2=N",Itr
2712 IF Itr=1 THEN GOTO 2384
2713 BEEP
2715 INPUT "OK TO STORE THIS DATA SET (1=Y,0=N)?",Oks
2716 IF Oks=1 THEN
2725 OUTPUT @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
2735 Alp2=Alp1+Alp2
2749 ELSE
2752 J=J+1
2755 END IF
2758 BEEP
2761 INPUT "WILL THERE BE ANOTHER RUN (1=Y,0=N)?",Go_on
2764 Nrun=J
2767 IF Go_on=0 THEN Repeat
2770 ELSE
2773 IF J=Nrun THEN Repeat
2776 END IF
2779 IF Ijob=1 THEN 2809
2782 IF Iw1=0 THEN
2785 ASSIGN @File TO *
2788 Ijob=1
2791 Iwd=1
2797 Im=2
2800 ASSIGN @File TO D_file$
2803 GOTO 1136
2806 END IF
2809 IF Ifg=0 THEN
2812 PRINT
2815  $S1 = (Nrun \cdot \sum y - \sum y \cdot \sum x) / (Nrun \cdot \sum x - \sum x^2)$ 
2818  $Ac = (\sum y - S1 \cdot \sum x) / Nrun$ 
2822 PRINT USING "10X," "Least-Squares Line for Ho vs q curve:" ""
2824 PRINT USING "10X," " Slope = ",MD.40E";S1
2827 PRINT USING "10X," " Intercept = ",MD.40E";Ac
2830 END IF
2833 BEEP
2843 INPUT "ENTER SAME TEMPORARY PLOT FILE NAME",Fplot$
2853 ASSIGN @Filep TO P_file$
2863 FOR I=1 TO Nrun
2873 ENTER @Filep;Qp,Ho
2883 Xc=LOG(Qp/Ho)

```

```

2884      Yc=LOG(Qp)
2885      Zx=Zx+Xc
2886      Zx2=Zx2+Xc**2
2887      Zxy=Zxy+Xc*Yc
2888      Zy=Zy+Yc
2889  NEXT I
2890  Bb=.75
2891  Aa=EXP((Zy-Bb*Zx)/Nrun)
2892  PRINT
2893  PRINT USING "10X","Least-squares line for q = a*delta-T^b"
2894  PRINT USING "12X","a = ",M2.40E";Aa
2895  PRINT USING "12X","b = ",M2.40E";Bb
2896  IF Ift=0 THEN
2897      IF Ipc=0 THEN
2898          Qps=2.5E+5
2899          IF Iic=0 THEN Hop=9326
2902          IF Iic=1 THEN Hop=10165*(.01905/Do)^(.33333)
2905      END IF
2908      IF Ipc=1 THEN
2911          Qps=7.5E+5
2914          IF Iic=0 THEN Hop=7176
2917          IF Iic=1 THEN Hop=7569*(.01905/Do)^(.33333)
2920      END IF
2923      Hos=Aa*(1/Bb)*Qps*((Bb-1)/Bb)
2926      IF Ipc=0 THEN Aas=2.32E+4
2929      IF Ipc=1 THEN Aas=2.59E+4
2930      Alpsm=.876      'SWENSEN DATA
2931      IF Iwil=0 THEN GOTO 2959
2933      Enrat=Alp2/Alpsm
2934      Enr=Hos/Hop
2938      PRINT
2947      PRINT USING "12X","Enhancement ratio (Del-T) = ",20.30";Enrat
2956  ELSE
2959      PRINT
2962      IF Ift=1 THEN
2965          Aas=2687.2      ' ZEBROWSKI (V = 0.4 m/s)
2968          Aas=2557.0*(.01905/Do)^(.33333)      ' VAN PETTEN (V = 0.25 m/s)
2971      END IF
2974      IF Ift=2 THEN Aas=9269.7*(.01905/Do)^(.33333)
2977      Edt=Aa/Aas
2980      Eq=Edt**(4/3)
2989  END IF
2995      BEEP
2998      PRINT
3001      PRINT USING "10X","NOTE: ",ZZ," data points were stored in file ",10
A";J,D_file$

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```

3007 BEEP
3013 PRINT
3016 PRINT USING "10X", NOTE: "",2Z,"" X-Y pairs were stored in data file "",10
A";J,Plot$
3031 BEEP
3073 ASSIGN @File TO *
3079 ASSIGN @Filep TO *
3080 PURGE "DUMMY"
3100 IF Iso=3 THEN CALL Wilsch(C1)
3116 END
3118 DEF FNPvst(Tc)
3121 COM /Fld/ Ift,Istu
3124 DIM K(8)
3127 IF Ift=0 THEN
3130 DATA -7.691234564,-25.08023696,-168.1706546,64.23285504,-118.9646225
3133 DATA 4.16711732,20.9750676,1.E9,6
3136 READ K(*)
3139 T=(Tc+273.15)/647.3
3142 Sum=0
3145 FOR N=0 TO 4
3148 Sum=Sum+K(N)*(1-T)^(N+1)
3151 NEXT N
3154 Br=Sum/(T*(1+K(5)*(1-T)+K(6)*(1-T)^2))-(1-T)/(K(7)*(1-T)^2+K(8))
3157 Pr=EXP(Br)
3160 P=22120000*Pr
3163 END IF
3166 IF Ift=1 THEN
3169 Tf=Tc*1.8+32+459.6
3172 P=10^((33.0655-4330.98/Tf-9.2635*LG(Tf)+2.0539E-3*Tf)
3175 P=P*101325/14.696
3178 END IF
3181 IF Ift=2 THEN
3184 A=9.394685-3066.1/(Tc+273.15)
3187 P=133.32*10^A
3190 END IF
3193 RETURN P
3196 FNEND
3199 DEF FNHfg(T)
3202 COM /Fld/ Ift,Istu
3205 IF Ift=0 THEN
3208 Hfg=2477200-2450*(T-10)
3211 END IF
3214 IF Ift=1 THEN
3217 Tf=T*1.8+32
3220 Hfg=7.0557857E+1-Tf*(4.838052E-2+1.2619048E-4*Tf)
3223 Hfg=Hfg*2326

```

```

3226 END IF
3229 IF Ift=2 THEN
3232   Tk=T+273.15
3235   Hfg=1.35264E+6-Tf*(6.38263E+2+Tk*.747462)
3238 END IF
3241 RETURN Hfg
3244 FNEND
3247 DEF FNMuw(T)
3250 COM /Fld/ Ift,Istu
3253 IF Ift=0 THEN
3256   A=247.8/(T+133.15)
3259   Mu=2.4E-5*10**A
3262 END IF
3265 IF Ift=1 THEN
3268   Mu=8.9629819E-4-T*(1.1094609E-5-T*5.566829E-8)
3271 END IF
3274 IF Ift=2 THEN
3277   Tk=1/(T+273.15)
3280   Mu=EXP(-11.0179+Tk*(1.744E+3-Tk*(2.80335E+5-Tk*1.12661E+8)))
3283 END IF
3286 RETURN Mu
3289 FNEND
3292 DEF FNUvst(Tt)
3295 COM /Fld/ Ift,Istu
3298 IF Ift=0 THEN
3301   P=FNpvst(Tt)
3304   T=Tt+273.15
3307   X=1500/T
3310   F1=1/(1+T*1.E-4)
3313   F2=(1-EXP(-X))**2.5*EXP(X)/X**.5
3316   B=.0015*F1-.000942*F2-.0004882*X
3319   K=2*P/(461.52*T)
3322   U=(1+(1+2*B*K)**.5)/K
3325 END IF
3328 IF Ift=1 THEN
3331   Tf=Tt*1.8+32
3334   U=13.955357-Tf*(.16127262-Tf*5.1726190E-4)
3337   U=U/16.018
3340 END IF
3343 IF Ift=2 THEN
3346   Tk=Tt+273.15
3349   P=FNpvst(Tt)
3352   U=133.95*Tk/P
3355 END IF
3358 RETURN U
3361 FNEND

```

```

3364 DEF FNCpw(T)
3367 COM /Fld/ Ift,Istu
3370 IF Ift=0 THEN
3373   Cpw=4.21100958-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7*T))
3376 END IF
3379 IF Ift=1 THEN
3382   Cpw=9.2507273E-1+T*(9.3400433E-4+1.7207792E-6*T)
3385 END IF
3388 IF Ift=2 THEN
3391   Tk=T+273.15
3394   Cpw=4.1868*(1.6884E-2+Tk*(3.35083E-3-Tk*(7.224E-6-Tk*7.61748E-9)))
3397 END IF
3400 RETURN Cpw*1000
3403 FNEND
3406 DEF FNRhow(T)
3409 COM /Fld/ Ift,Istu
3412 IF Ift=0 THEN
3415   Ro=999.52346+T*(1.01269-T*(5.482513E-3-T*1.234147E-5))
3418 END IF
3421 IF Ift=1 THEN
3424   Ro=1.6207479E+3-T*(2.2186346+T*2.3578291E-3)
3427 END IF
3430 IF Ift=2 THEN
3433   Tk=T+273.15-338.15
3436   Vf=9.24848E-4+Tk*(6.2796E-7+Tk*(9.2444E-10+Tk*3.057E-12))
3439   Ro=1/Vf
3442 END IF
3445 RETURN Ro
3448 FNEND
3451 DEF FNPrw(T)
3454 Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
3457 RETURN Prw
3460 FNEND
3463 DEF FNKw(T)
3466 COM /Fld/ Ift,Istu
3469 IF Ift=0 THEN
3472   X=(T+273.15)/273.15
3475   Kw=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
3478 END IF
3481 IF Ift=1 THEN
3484   Kw=8.2095238E-2-T*(2.2214286E-4+T*2.3809524E-8)
3487 END IF
3490 IF Ift=2 THEN
3493   Tk=T+273.15
3496   Kw=4.1868E-4*(519.442+.320920*Tk)
3499 END IF

```

```

3502 RETURN Kw
3505 FNEND
3508 DEF FNTanh(x
3511 P=EXP(x)
3514 Q=EXP(-x)
3517 Tanh=(P-Q)/(P+Q)
3520 RETURN Tanh
3523 FNEND
3526 DEF FNTvsv(U)
3529 COM /Cc/ C(7)
3532 T=C(0)
3535 FOR I=1 TO 7
3538 T=T+C(I)*U**I
3541 NEXT I
3547 RETURN T
3550 FNEND
3553 DEF FNHf(T)
3556 COM /F1d/ Ift,Istu
3559 IF Ift=0 THEN
3562 Hf=T*(4.203849-T*(5.88132E-4-T*4.55160317E-6))
3565 END IF
3568 IF Ift=1 THEN
3571 Tf=T*1.8+32
3574 Hf=8.2076571+Tf*(.19467857+Tf*1.3214286E-4)
3577 Hf=Hf*2.325
3580 END IF
3583 IF Ift=2 THEN
3586 Hf=250 ! TO BE VERIFIED
3589 END IF
3592 RETURN Hf*1000
3595 FNEND
3598 DEF FNGrad(T)
3601 Grad=37.9853+.104388*T
3604 RETURN Grad
3607 FNEND
3610 DEF FNTvsp(P)
3613 Tu=190
3616 Tl=10
3619 Ta=(Tu+Tl)*.5
3622 Pc=FNpvt(Ta)
3625 IF ABS((P-Pc)/P)>.0001 THEN
3628 IF Pc<P THEN Tl=Ta
3631 IF Pc>P THEN Tu=Ta
3634 GOTO 3619
3637 END IF
3640 RETURN Ta

```

```

6643  FNEND
6646  DEF FNSigma(T)
6649  X=647.3-T-273.15
6652  S=.1160936607*(1+.93*X)+1.121404688E-3-5.75290518E-6*X+1.28627465E-9*X2-1
.14971929E-11*X3
6655  RETURN S+.001*X2
6658  FNEND
6666  SUB Wilson(C1)
6669  COM /Wils/ Nrun,Itn,Iwth,Imc,Ife,Ijob,Iwd,Ifg,Ipc,Ifto,Iw1,Ih1,Ioc,Inam,R
cu,Rexp,Rm,Ax
6672  COM /Fld/ Ift,Istu
6673  COM /Geom/ D1,D2,D1,Do,L,L1,L2
6674  COM /Fric/ Istuo,Inn,Iwtho,Vw,Vws,Inamo
6676  DIM Emf(20),Bvo(42),Bam(42),Eata(42),Ear(42,7),Fma(42),T1a(42),T2a(42)
6678  IF Ioc=0 THEN
6679      PRINT USING "16x","Nusselt theory is used for Ho""
6680  ELSE
6681      PRINT USING "16x","Fujii correlation used for Ho""
6682  END IF
6683  BEEP
6684  INPUT "RE-ENTER DATA FILE BEING PROCESSED",D_file$
6685  BEEP
6686  INPUT "GIVE A NAME FOR XY PLOT-DATA FILE",Plot$
6687  CREATE BDAT Plot$,10
6688  ASSIGN @Io_path TO Plot$
6689  Jj=0
6690  ASSIGN @File TO D_file$
6691  ENTER @File:Ifg,Inn
6692  IF Istuo=0 THEN
6693      ENTER @File:Ddd,Ddd,Ddd,Ddd
6694  ELSE
6695      IF Ifg=0 THEN ENTER @File:Iwt
6696      IF Ifg=1 THEN ENTER @File:Fp,Fw,Fh
6697  END IF
6698  IF Jj=0 THEN
6699      IF Ih1=0 THEN C1=.027
6700      IF Ih1=1 THEN C1=1.00
6701      IF Ih1=2 THEN C1=1.00
6702      IF Ifg=0 THEN Alp=1.2
6703      IF Ifg=1 THEN Alp=2.6
6704      IF Ift=2 AND Ifg=1 THEN Alp=5.0
6705  END IF
6706  J=0
6707  Sx=0
6708  Sy=0
6709  Sxs=0

```

```

6919 Exy=0
6921 READ DATA FROM A USER-SPECIFIED FILE IF INPUT MODE (Im) = 2
6925 IF Jj=0 THEN
6926     IF Istu=0 THEN
6931         ENTER @File;Bvol,Bamp,Etp,Fm,T1,T2,Odd,Odd,Emf(*)
6932     ELSE
6934         ENTER @File;Bvol,Bamp,Utran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),F
m,T1,T2,Png,Pwater
6936     END IF
6938     Bvo(J)=Bvol
6939     Bam(J)=Bamp
6940     Eata(J)=Etp
6943     Ear(J,0)=Emf(0)
6946     Ear(J,1)=Emf(1)
6949     Ear(J,2)=Emf(2)
6952     Ear(J,3)=Emf(3)
6955     Ear(J,4)=Emf(4)
6956     IF Istu=1 THEN GOTO 6961
6958     Ear(J,5)=Emf(5)
6959     Ear(J,6)=Emf(6)
6960     Ear(J,7)=Emf(7)
6961     Fma(J)=Fm
6962     T1a(J)=T1
6964     T2a(J)=T2
6967 ELSE
6970     Bvol=Bvo(J)
6973     Bamm=Bam(J)
6976     Etp=Eata(J)
6979     Emf(0)=Ear(J,0)
6982     Emf(1)=Ear(J,1)
6985     Emf(2)=Ear(J,2)
6988     Emf(3)=Ear(J,3)
6991     Emf(4)=Ear(J,4)
6992     IF Istu=1 THEN GOTO 6997
6994     Emf(5)=Ear(J,5)
6995     Emf(6)=Ear(J,6)
6996     Emf(7)=Ear(J,7)
6997     Fm=Fma(J)
6998     T1=T1a(J)
7000     T2=T2a(J)
7003 END IF
7004 IF Istu=0 THEN
7006     Tsat=FNTvsv57((Emf(0)+Emf(1))/2.)
7007     Tsat=Tsats-273.15
7009     T1=FNTvsv58(Emf(3))
7010     T01=FNTvsv58(Emf(4))

```

```

7012      T1=T1-273.15
7013      Ts1=Ts1-273.15
7015      Etp1=Emf(3)+Etp/20.
7016      Otdc=2.9331E-2-1.52464E-5*Etp1+1.21721E-10*Etp12-5.1164E-15*Etp13+3.2
201E-19*Etp14
7017      Tris=Otdc*Etp/10.
7018      To=T1+Tris
7019  ELSE
7020      Tsat=FNTvsv(Emf(0))
7021      T1=FNTvsv(Emf(2))
7022      Grad=FNGrad((T1+Ts1)*.5)
7023      To=T1+ABS(Etp/(10*Grad*.1.E+6)
7024  END IF
7025  CALCULATE THE LOG-MEAN-TEMPERATURE DIFFERENCE
7026  IF Istu=0 AND Itm=0 THEN
7027      Tf=T1
7028      Tl=Ts1
7029  END IF
7030  IF Itm=1 THEN
7031      Tf=T1
7032      Tl=T2
7033  END IF
7034  IF Itm=2 THEN
7035      Tf=T1
7036      Tl=Ts
7037  END IF
7038  Tavg=(Tf+Tl)*.5
7040  Trise=Tl-Tf
7041  Lmtd=Trise/LOG((Tsat-Tf)/(Tsat-Tl))
7042  Ift=0
7043  Cpw=FNCPw(Tavg)
7044  Rhow=FNRRhow(Tavg)
7045  Kpw=FNKw(Tavg)
7048  Muwa=FNMuw(Tavg)
7051  Rnw=FNPRw(Tavg)
7054  Ift=If to
7055  IF Istu=0 THEN
7057      Mdt=(6.7409*Fm+13.027)/1000.
7060      Md=Mdt*(1.0365-Tf*(1.96644E-3-Tf*5.252E-6))/1.0037
7061  ELSE
7062      Mdt=1.04805E-2+6.80932E-3*Fm
7063      Md=Mdt*(1.0365-Tf*(1.96644E-3-Tf*5.252E-6))/1.995434
7065  END IF
7066  Vf=Md/Rhow
7067  Vw=Vf/(PI*D12/4)
7068  Jws=Vw*(D1/1.27E-2)2

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7069 Tcon=FNTfnic(Trise)
7070 Trise=Tcon
7071 Tcon=FNTvsv58/Emf(7)
7072 Tcon=Tcon-273.15
7074 Cpse=FNCPw(Tcon+Tsats*.5)
7076 Hfg=FNHfg(Tsats)
7078 Q1=500
7080 Qloss=Q1/(100-25)*(Tsats-Troom) ! TO BE MODIFIED
7082 Mdv=0
7084 Ep=(Bvol*100)^2/5.76
7085 Hsc=Cpse*(Tsats-Tcon)
7086 Mdv=((Ep-Qloss)-Mdv*Hsc)/Hfg
7088 IF ABS((Mdv-Mdv)/Mdv)>.01 THEN
7090     Mdv=(Mdv+Mdv)*.5
7092     GOTO 7086
7094 END IF
7096 Mdv=(Mdv+Mdv)*.5
7098 Vg=FNVst(Tsats)
7100 Vv=Mdv*Vg/Ax
7108 Q=Md*Cpw*Trise
7111 Qp=Q/(PI*Do*L)
7114 Uo=Qp/Lmtd
7117 Re=Rhow*Vv*Di/Muwa
7120 Fe1=0
7123 Fe2=0
7126 Cf=1.
7127 Prwf=Prw
7128 Re1f=Re
7129 Ift=0
7131 Two=Tsats-5
7132 Tfilm=Tsats/3+Two*2/3
7135 kf=FNkw(Tfilm)
7138 Rhof=FNRhof(Tfilm)
7141 Muf=FNMuw(Tfilm)
7144 Hfgp=FNHfg(Tsats)+.68*FNCPw(Tfilm)*(Tsats-Two)
7147 New=kf*(Rhof^2*9.81*Hfgp/(Muf*Do*Qp))^-.3333
7148 New=(kf^3*9.81*Hfgp*Rhof^2/(Muf*Do*(Tsats-Two)))^-.25
7150 IF Ioc=1 THEN
7153 New=kf*((9.81*Hfgp/Qp)^.25)*((Muf*Do)^(-.375))*(Rhof^.625)*(Vv^.125)
7154 New=(9.81*Hfgp/(Tsats-Two))^2*kf^.8*Vv^.1*Rhof^.5/(Do*Muf)^.3
7156 END IF
7159 Ho=Alp*New
7162 Twoc=Tsats-Qp/Ho
7165 IF ABS((Twoc-Two)/Twoc)>.001 THEN
7168     Two=Twoc
7171     GOTO 7132

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7174 END IF
7175 Re*pi=Re*p
7184 IF Ihi=0 THEN
7186   Omega=Re/Re*pi*Prw*.3333*Qf
7187 END IF
7188 IF Ihi=1 THEN
7189   Sra=.88-(1.24/(4.+Prwf))
7190   Srb=.333333+.5*EXP(-6*Prwf)
7191   Omega=(5.+.015*Reif*Sra*Prwf*Srb)
7192 END IF
7193 IF Ihi=2 THEN
7194   Eps1=(1.92*LGT(Re)-1.64)**(-2)
7195   Ppk1=1.+3.4*Eps1
7196   Ppk2=11.7+1.8*Prwf*(-1/3)
7197   Pp1=(Eps1/8)*Re*Prw
7198   Pp2=(Ppk1+Ppk2*(Eps1/8)*.5*(Prw*.6666-1))
7199   Omega=Pp1/Pp2
7200 END IF
7202 H1=Kw/D1*O1*Omega
7203 IF Ife=0 THEN 7216
7204 P1=PI*(D1+D1)
7205 P2=PI*(D1+D2)
7206 A1=(D1-D1)*PI*(D1+D1)*.5
7207 A2=(D2-D1)*PI*(D1+D2)*.5
7208 M1=(H1*P1/(Kdu*A1))**.5
7209 M2=(H1*P2/(Kdu*A2))**.5
7210 Fe1=FNtanh(M1*L1)/(M1*L1)
7213 Fe2=FNtanh(M2*L2)/(M2*L2)
7216 Dt=Q/(PI*D1*(L+L1*Fe1+L2*Fe2)*H1)
7217 IF Ihi=0 THEN
7219   Muw1=FNMuw(Tavg+Dt)
7222   Cfc=(Muwa/Muw1)**.14
7225   IF ABS((Cfc-Cf)/Cfc)>.001 THEN
7228     Cf=(Cf+Cfc)*.5
7231     GOTO 7184
7232   END IF
7234 END IF
7235 IF Ihi=1 THEN
7236   Prwfc=FNPrw(Tavg+Dt)
7237   Reifc=Vw*D1*FNrho(Tavg+Dt)/FNMuw(Tavg+Dt)
7239   IF ABS((Prwfc-Prwf)/Prwfc)>.001 OR ABS((Reifc-Reif)/Reifc)>.001 THEN
7240     Prwf=(Prwfc+Prwf)/2.
7241     Reif=(Reifc+Reif)/2.
7242     GOTO 7184
7243   END IF
7245 END IF

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7246 Ift=Ifto
7247 x=Do*New*L/((Omega*Kw*(L+L1*Fe1+L2*Fe2))
7248 y=New*(1/Uo-Rm)
7249 COMPUTE COEFFICIENTS FOR THE LEAST-SQUARES-FIT STRAIGHT LINE
7250 IF Jp=1 THEN OUTPUT @Io_path;X,Y
7252 Sx=Sx+x
7255 Sy=Sy+y
7258 Sxs=Sxs+X*X
7261 Sxy=Sxy+X*Y
7264 IF Im=1 AND Jj=0 THEN OUTPUT @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(
*)
7267 J=J+1
7270 IF J Nrun THEN 6925
7273 S1=(Nrun*Sxy-Sy*Sx)/(Nrun*Ss-Sx^2)
7276 IF Iw1=2 THEN
7277     IF Ih1=0 THEN S1=1/.027
7278     IF Ih1=1 THEN S1=1/1.00
7289     IF Ih1=2 THEN S1=1/1.00
7291 END IF
7294 Ac=(Sy-S1*Sx)/Nrun
7297 C1c=1/S1
7300 Alpc=1/Ac
7303 Jj=Jj+1
7306 IF Jp=1 THEN Jp=2
7309 Cerr=ABS((C1c-C1)/C1c)
7312 Aerr=ABS((Alpc-Alp)/Alpc)
7315 IF Cerr .001 OR Aerr .001 THEN
7318     C1=(C1c+C1)*.5
7321     Alp=(Alpc+Alp)*.5
7324     BEEP
7327     IF Ijob=1 THEN 6907
7330 ELSE
7333     IF Jp=0 THEN Jp=1
7336 END IF
7339 IF Jp=1 THEN 6874
7342 C1=(C1+C1c)*.5
7345 PRINT
7346 IF Ih1=0 THEN
7348     PRINT USING "10X,""C1 (based on Sieder-Tate) = "",Z.4D";C1
7349 END IF
7350 IF Ih1=1 THEN
7351     PRINT USING "10X,""C1 (based on Sleicher-Rouse) = "",Z.4D";C1
7352     PRINT USING "10X,""Re exponent for Sleicher-Rouse = "",D.000";Sra
7353 END IF
7354 IF Ih1=2 THEN
7355     PRINT USING "10X,""C1 (based on Petukhov-Popov) = "",Z.4D";C1

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7356 END IF
7357 IF Ipc=0 THEN
7358     PRINT USING "0X", "Alpha (based on Nusselt (Tdel)) = ",2.40";Alp
7359 END IF
7360 IF Ipc=1 THEN
7361     PRINT USING "0X", "Alpha (based on Fujii (Tdel)) = ",2.40";Alp
7362 END IF
7363 IF Inam=5 OR Inam=6 THEN
7364     IF Ini=0 THEN
7365         IF Ipco=0 AND Inn=0 THEN Alpsm=.8218      INO INSERT,VACUUM,S-T
7366         IF Ipco=1 AND Inn=0 THEN Alpsm=.7793      INO INSERT,ATMOSPHERIC,S-T
7367         IF Ipco=0 AND Inn=3 THEN Alpsm=.7854      IHEATEX,VACUUM,S-T
7368         IF Ipco=1 AND Inn=3 THEN Alpsm=.7769      IHEATEX,ATMOSPHERIC,S-T
7369     END IF
7370     IF Ini=1 THEN
7371         IF Ipco=0 AND Inn=0 THEN Alpsm=.8613      INO INSERT,VACUUM,S-R
7372         IF Ipco=1 AND Inn=0 THEN Alpsm=.8218      INO INSERT,ATMOSPHERIC,S-R
7373         IF Ipco=0 AND Inn=3 THEN Alpsm=.7791      IHEATEX,VACUUM,S-R
7374         IF Ipco=1 AND Inn=3 THEN Alpsm=.7929      IHEATEX,ATMOSPHERIC,S-R
7375     END IF
7376     IF Ini=2 THEN
7377         IF Ipco=0 AND Inn=0 THEN Alpsm=.8205      INO INSERT,VACUUM,P-P
7378         IF Ipco=1 AND Inn=0 THEN Alpsm=.7654      INO INSERT,ATMOSPHERIC,P-P
7379         IF Ipco=0 AND Inn=3 THEN Alpsm=.7670      IHEATEX,VACUUM,P-P
7380         IF Ipco=1 AND Inn=3 THEN Alpsm=.7708      IHEATEX,ATMOSPHERIC,P-P
7381     END IF
7382 END IF
7383 IF Inam=4 THEN
7384     IF Ipco=1 THEN Alpsm=.876      ISWENSEN DATA BASED ON DEL-T
7385 END IF
7386 IF Inam=0 OR Inam=3 THEN
7387     IF Ipco=0 THEN Alpsm=.83      IUP MISTV103
7388     IF Ipco=1 THEN Alpsm=.88      IUP 3MTHSTAG5
7389     IF Ift=1 THEN Alpsm=.677      IVAN PETTEN (V = 0.25 m/s)
7390     IF Ift=2 THEN Alpsm=1.262
7391 END IF
7392 IF Inam=1 THEN      IMITROU ALPHA FOR P-P FROM REPROCESSING
7393     IF Ipco=0 THEN Alpsm=.8437
7394     IF Ipco=1 THEN Alpsm=.8418
7395 END IF
7396 Et=Alp/Alpsm
7397 Eq=Et^1.333333
7398 PRINT USING "10X","Enhancement (q) = ",00.30";Eq
7399 PRINT USING "10X","Enhancement (Del-T) = ",00.30";Et
7400 ASSIGN @File TO *
7401 SUBEND

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7721 DEF FNTvsvSS(V)
7731 COM /CcSS/ TSS(S)
7741 T=TSS(0)
7751 FOR I=1 TO 5
7761     T=T+TSS(I)*VI
7771     NEXT I
7781 RETURN T
7791 FNEND
7801 DEF FNTvsvS6(V)
7811 COM /CcS6/ TS6(S)
7821 T=TS6(0)
7831 FOR I=1 TO 5
7841     T=T+TS6(I)*VI
7851     NEXT I
7861 RETURN T
7871 FNEND
7881 DEF FNTvsvS7(V)
7891 COM /CcS7/ TS7(S)
7901 T=TS7(0)
7911 FOR I=1 TO 5
7921     T=T+TS7(I)*VI
7931     NEXT I
7941 RETURN T
7951 FNEND
7961 DEF FNTvsvS8(V)
7971 COM /CcS8/ TS8(S)
7981 T=TS8(0)
7991 FOR I=1 TO 5
8001     T=T+TS8(I)*VI
8011     NEXT I
8021 RETURN T
8031 FNEND
8100 DEF FNTfric(Tcor)
8110 COM /Fric/ Istuo,Inn,Iwtho,Vw,Vws,Inamo
8115 IF Istuo=0 AND Iwtho=0 THEN 'SWENSEN FRICTION FAC. FOR COPPER TUBE
8120     IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(-2.73E-4+1.75E-4*Vw+9.35E-4*Vw2-1.9
8130     IF Inn=1 THEN Tcor=Tcor-(-6.44E-5+1.71E-3*Vw+4.45E-4*Vw2+4.07E-5*Vw3)
8140     IF Inn=2 THEN Tcor=Tcor-(-3.99E-4+2.75E-3*Vw+1.45E-3*Vw2+8.16E-5*Vw3)
8150     IF Inn=3 THEN Tcor=Tcor-(8.57E-5+1.23E-3*Vw+1.08E-3*Vw2+8.16E-5*Vw3)
8160 END IF
8170 IF Istuo=0 AND Iwtho=2 THEN 'OKEEFE FRIC. FAC. FOR SMOOTH TITANIUM TUBE.
8180     IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(-4.62E-5-7.53E-4*Vw+1.80E-3*Vw2-8.8
8190     IF Inn=3 AND Inamo=5 THEN Tcor=Tcor-(2.09E-4+9.74E-4*Vw+2.12E-3*Vw2-3.
8190     31E-5*Vw3)

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8191      IF Inn=3 AND Inamo=6 THEN Tcor=Tcor-(1.9555E-4+3.9721E-3*Vw+3.127E-4*Vw
      2+3.519E-4*Vw^3)
8200  END IF
8210  IF Istuo=0 AND Iwtho=1 THEN FRICTION FACTORS FOR LPD KORODENSE
8220      IF Inn=0 AND Vw<.5 THEN Tcor=Tcor-(-3.386E-4+1.88E-3*Vw+6.013E-4*Vw^2-4
      .133E-5*Vw^3)
8230      IF Inn=3 THEN Tcor=Tcor-(2.089E-4+9.202E-4*Vw+1.893E-3*Vw^2-2.781E-5*Vw
      ^3)
8240  END IF
8242  IF Istuo=0 AND Iwtho=3 THEN FRICTION FACTORS FOR MHT KORODENSE
8244      IF Inn=0 AND Vw<.5 THEN Tcor=Tcor-(6.79E-5+1.632E-3*Vw+8.409E-4*Vw^2+1.
      111E-4*Vw^3)
8246      IF Inn=3 THEN Tcor=Tcor-(2.564E-4+6.263E-4*Vw+2.603E-3*Vw^2+7.930E-6*Vw
      ^3)
8247  END IF
8250  IF Istuo=1 THEN
8260      IF Inn=0 THEN Tcor=Tcor-(.0138+.001*Vw^2)
8270      IF Inn=1 THEN Tcor=Tcor-.004*Vws^2
8280      IF Inn=2 THEN Tcor=Tcor-.004*Vws^2
8290  END IF
8300  RETURN Tcor
8310  FEND

```

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